SCALING CONSIDERATIONS FOR THERMOELECTRIC GENERATORS

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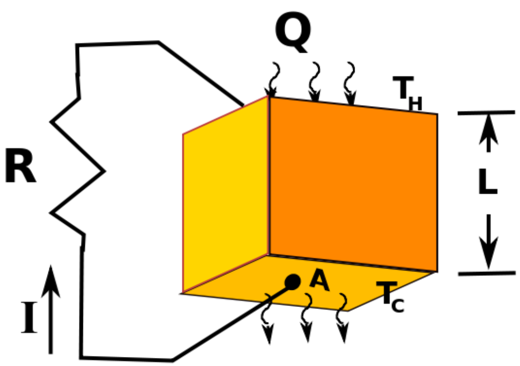
TE MATERIAL PROPERTIES S, λ, σ



IOFFE (1950's)*
ANALYSIS OF GENERATION EFFICIENCY FOR A PELLET

ASSUMPTIONS:

1. **UNIFORM CROSS-SECTION A**
2. **UNIFORM LENGTH L**
3. **CONSTANT MATERIAL PARAMETERS, S, λ, σ**
4. **RESISTIVE LOAD MATCHED TO INTERNAL RESISTANCE (YIELDS MAXIMUM POWER TRANSFER)**

IMPLICATIONS:

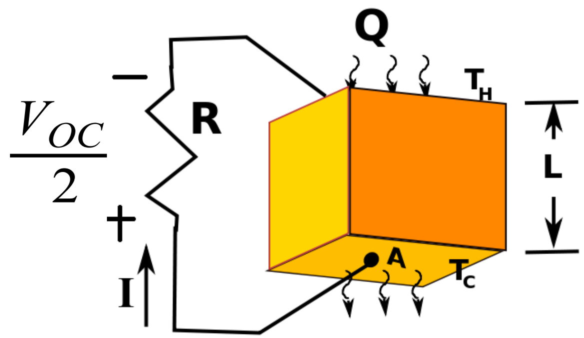
1 **CARNOT LIMIT**
2. **NO DEPENDENCE ON GEOMETRY**
3. **TE MATERIALS APPEAR IN SAME RELATION**

$$\eta = \frac{P}{Q} = \frac{\Delta T}{T_H} \times \frac{\sqrt{1+\frac{S^2\sigma T}{\lambda}}-1}{\sqrt{1+\frac{S^2\sigma T}{\lambda}}+\frac{T_C}{T_H}}$$

* A.F. Ioffe, Semiconductor Thermoelectrics and Thermoelectric Cooling, Infosearch, LTD, London, 1957.

A SINGLE TE MATERIAL PARAMETER $Z=\sigma S^2/\lambda$

$$\eta = \frac{\Delta T}{T_H} \times \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{T_C}{T_H}}$$



WHAT ABOUT POWER?

OPEN CIRCUIT GENERATED VOLTAGE $V_{OC} = S\Delta T$

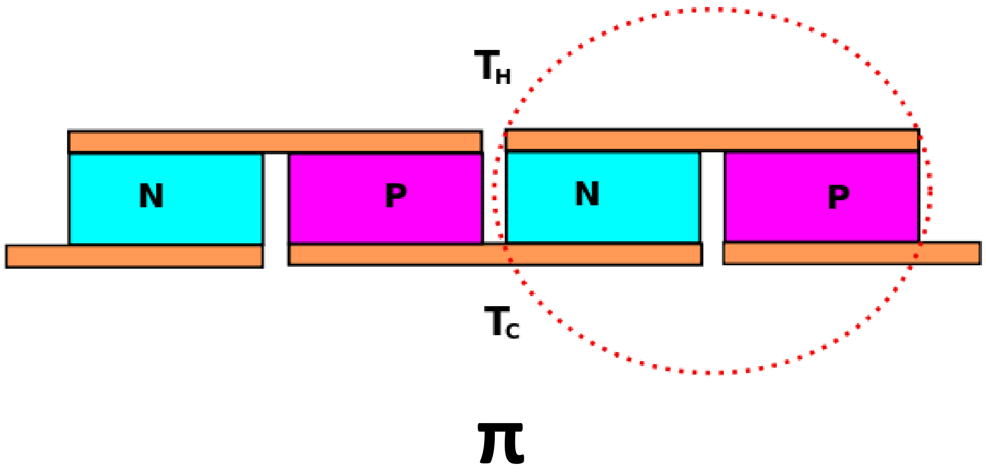
RESISTIVE LOAD FOR MAX POWER $R = \frac{L}{\sigma A}$

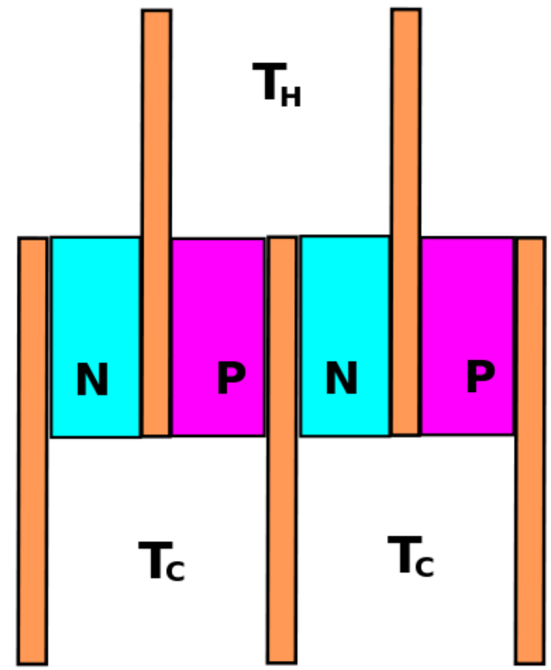
$$P = \frac{\sigma S^2 \Delta T^2 A}{4L}$$

IMPLICATIONS:

1. **GEOMETRY MATTERS**
2. **RELEVANT TE MATERIAL PROPERTIES ARE σ AND S. POWER FACTOR = σS^2**

REAL GENERATORS NEED CONNECTIONS
(and connections always introduce parasitics)



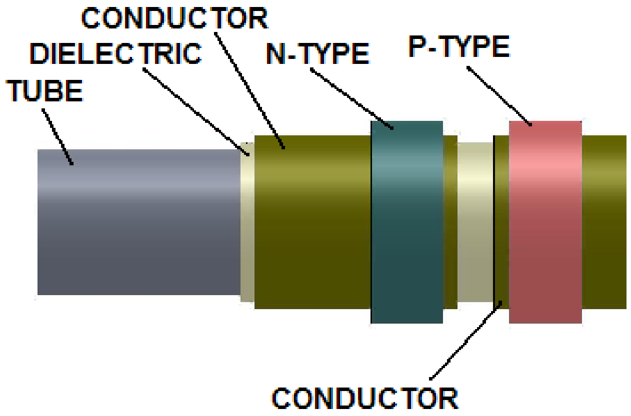


ELECTRIC CURRENT FLOW AND HEAT ENERGY FLUX IS APPROXIMATELY PARALLEL IN THE THERMOELEMENTS

---- NOT SO IN THE CONNECTIONS.

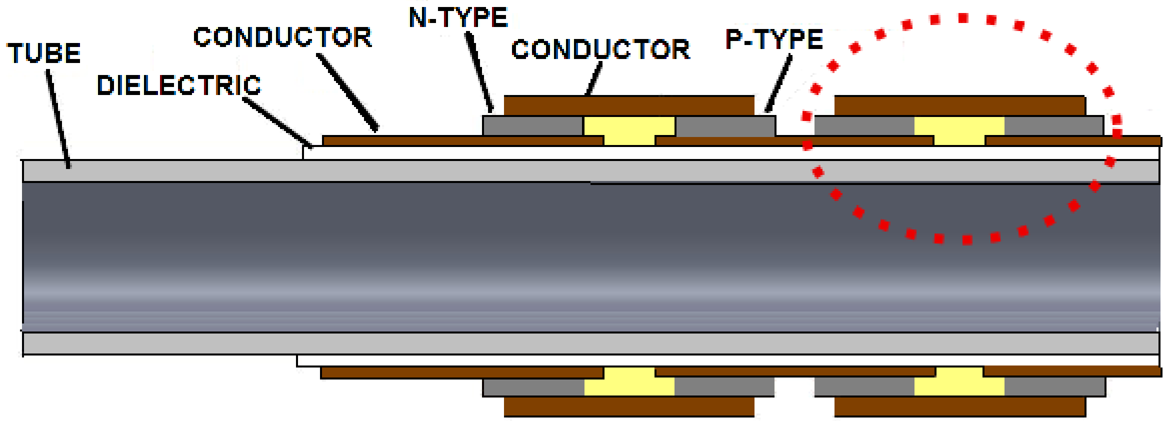
OERSTED

MOTIVATION: SPRAYCAST TUBULAR TEG FOR USE IN HEAT EXCHANGERS

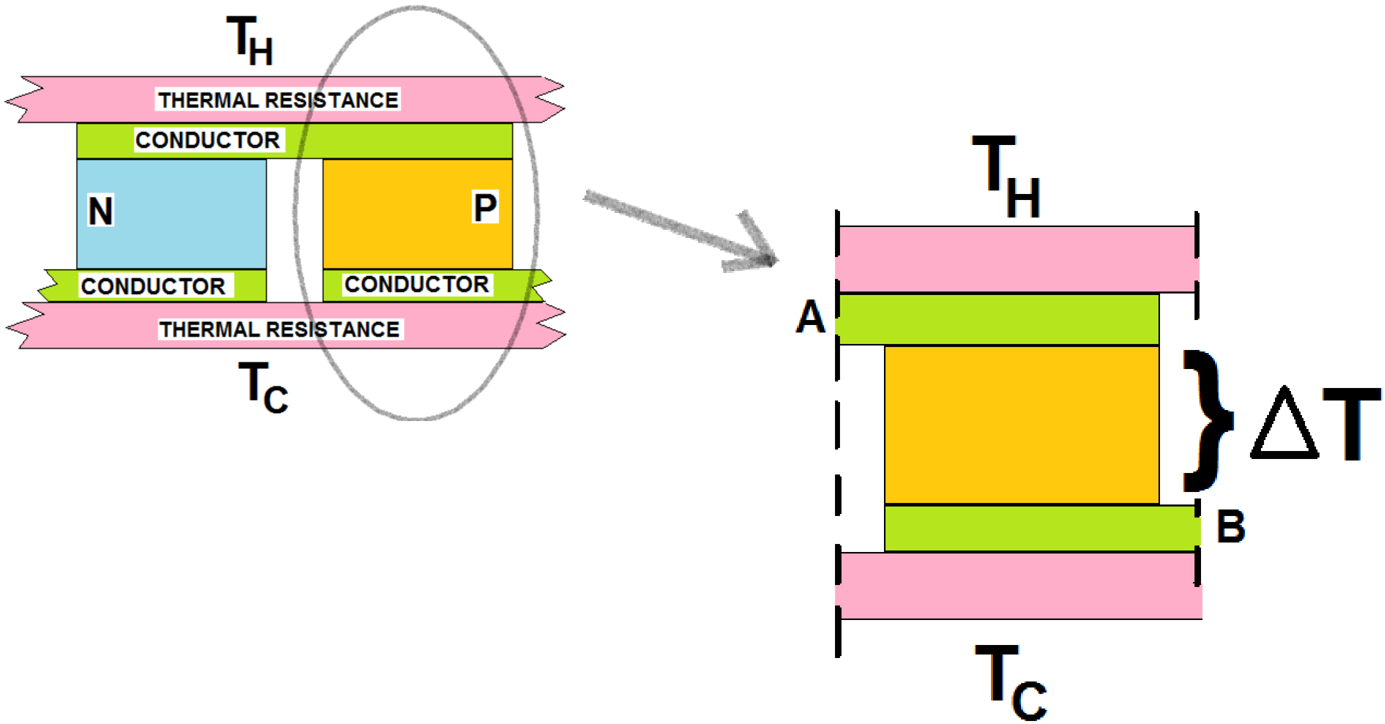


THERMOELECTRIC LAYERS --- HOW THICK?
HOW LONG?

CONDUCTORS: HOW THICK? HOW LONG?

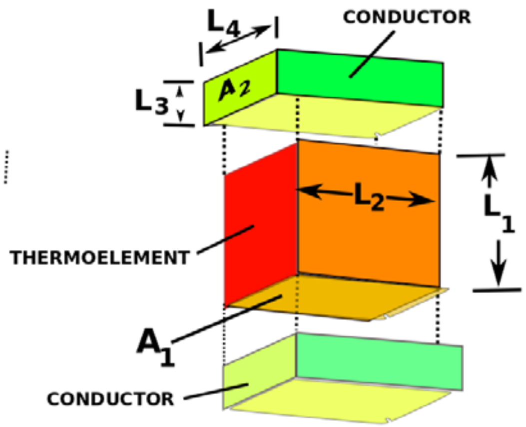


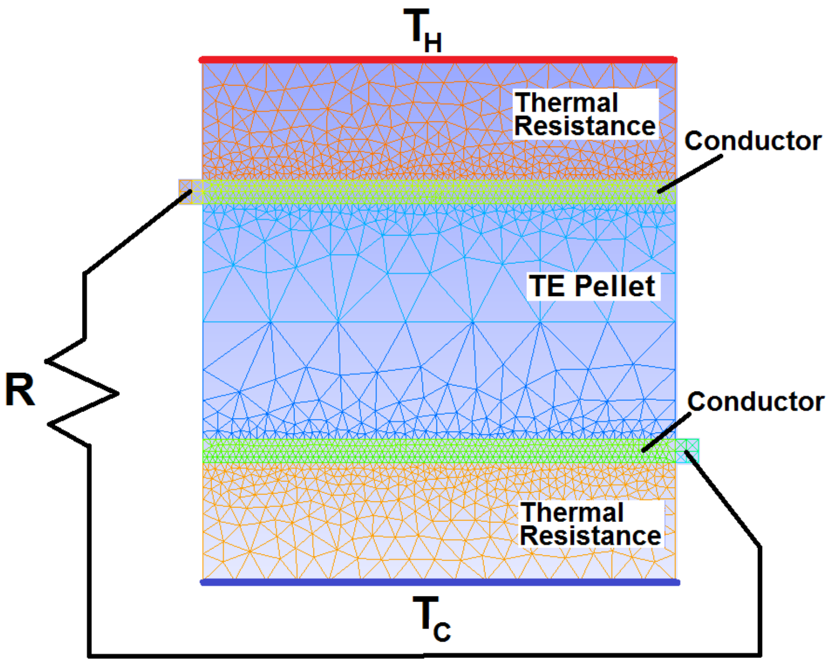
PARASITICS THAT REDUCE POWER GENERATION



THERMAL PARASITIC – ANYTHING THAT REDUCES ΔT
ELECTRICAL PARASITIC – ANYTHING THAT INCREASES RESISTANCE BETWEEN A AND B

GENERATION FROM A SINGLE ELEMENT



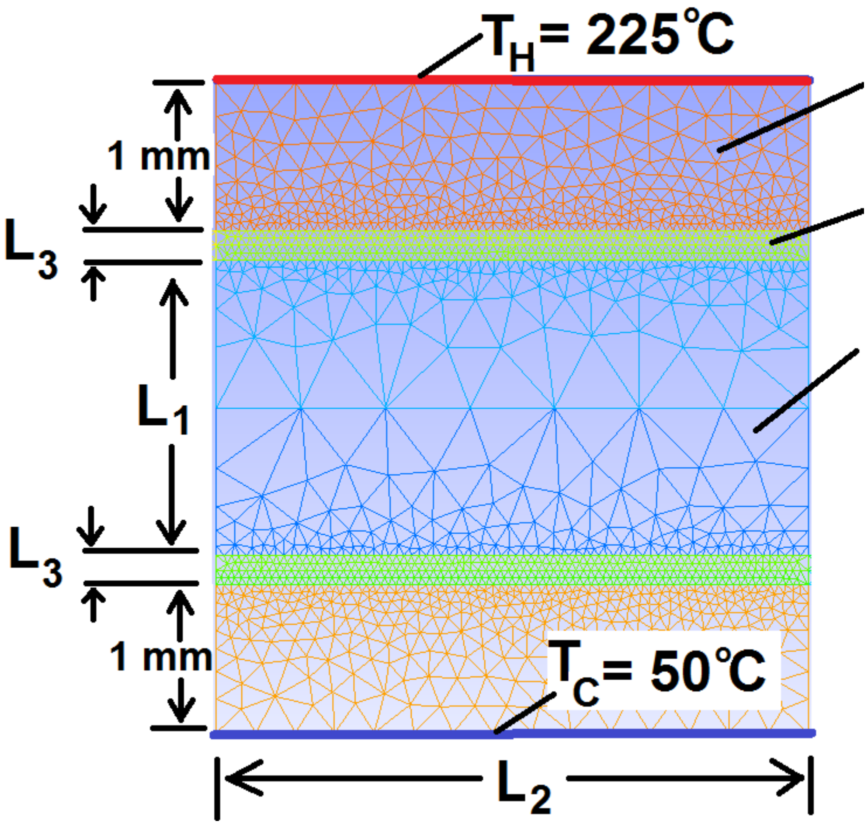


EVERYTHING SCALES WITH THE L_4 DIMENSION. SO OPTIMIZATION CAN TAKE PLACE IN 2D

2D FE MODEL AFTER PEREZ-APARACIO ET AL*. ALLOWS EXPRESSION OF SEEBECK, JOULE, THOMPSON, PELTIER EFFECTS & THERMAL ENERGY CARRIED BY ELECTRONS.

* J.L. Perez-Aparacio, R.L. Taylor and D. Gavela, “Finite Element Analysis of Nonlinear Fully Coupled Thermoelectric Materials”, **Computational Mechanics** (2007) 40:35-45.

SIMULATION PARAMETERS



THERMAL RESISTANCE MODEL
σ=0, S=0, λ=1.42 W/mK

COPPER
$\sigma = 5.8 X 10^{7}\ \Omega^{-1} m^{-1}$, λ=401 W/mK,
$S = 1.84 X 10^{-6}$ V/K

P-DOPED BiSbTe* (Temp. in °C)

$\sigma(T) = 1.14 X 10^{5} – 596T + 1.25T^{2}\ \Omega^{-1} m^{-1}$
$\lambda(T) = 1.47 – 3.78 X 10^{-3} T + 2.76 X 10^{-5} T^{2}$ W/mK
$S(T) = 2 X 10^{-4} + 6.29 X 10^{-7} – 3.25 X 10^{-9} T^{2}$ V/K

L_4 = 1 mm in all cases
Variables: L_1, L_2, L_3

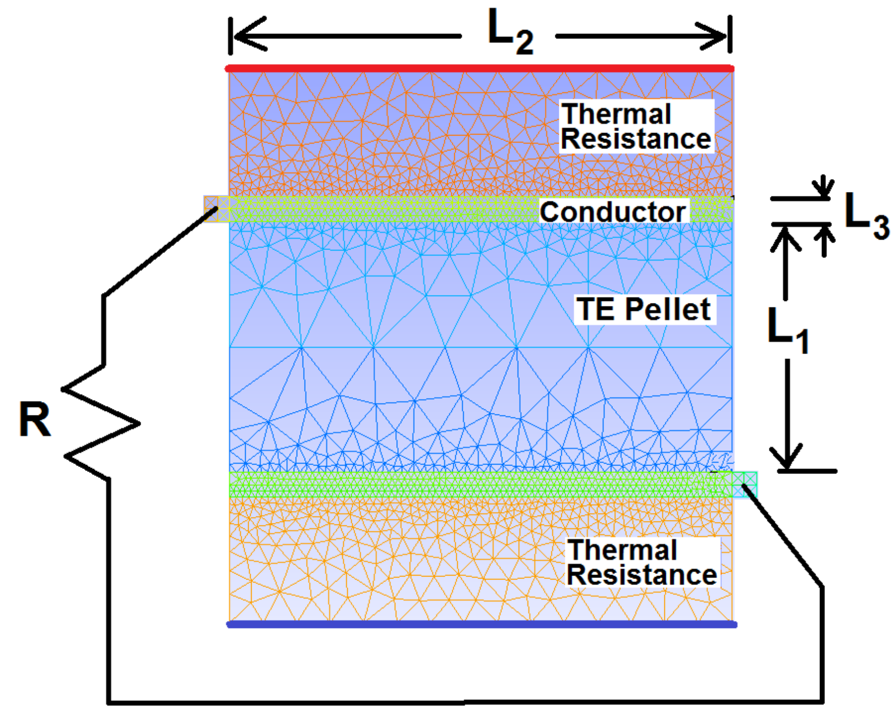
*B. Poudel, Q. Hao, Y. Ma, Y. Lan, A. Minnich, B. Yu, X. Yan, D. Wang, A. Muto, D. Vashaee, X Chen, J Liu, M. Dresselhous, G. Chen, Z. Ren, "High-Thermoelectric Performance of Nanostructured Bismuth Antimony Telluride Bulk Alloys", **Science** (2008), 320: 634-638.

PROCEDURE

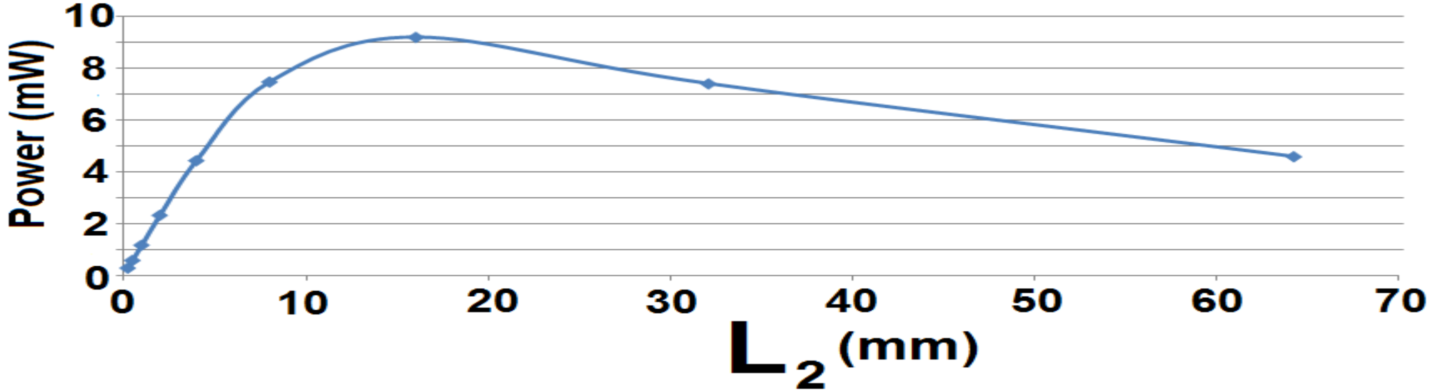
1. CHOOSE A GEOMETRY L1, L2, L3
2. PLACE OPEN CIRCUIT ACROSS PELLET AND CALCULATE V_{OC}
3. CONNECT A SHORT ACROSS PELLET AND CALCULATE I_{SC}
4. CALCULATE THE RESISTANCE THAT YIELDS MAX POWER

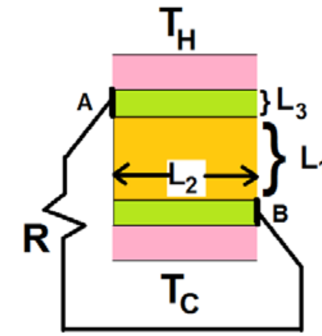
$$R = \frac{V_{OC}}{I_{SC}}$$

5. USING THIS R, CALCULATE MAXIMUM POSSIBLE POWER AND CORRESPONDING EFFICIENCY

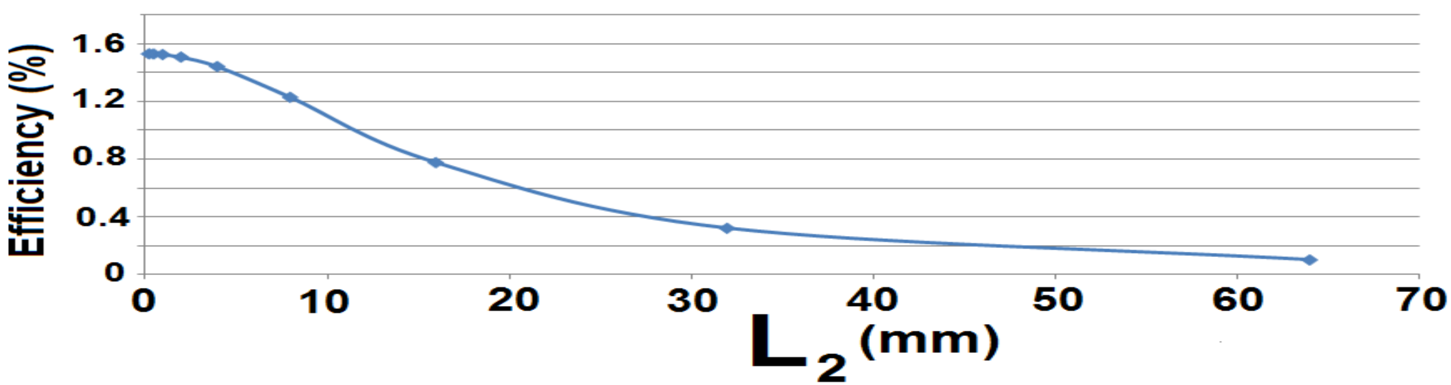


POWER AND EFFICIENCY (L_1=1 mm, L_3=0.1 mm)

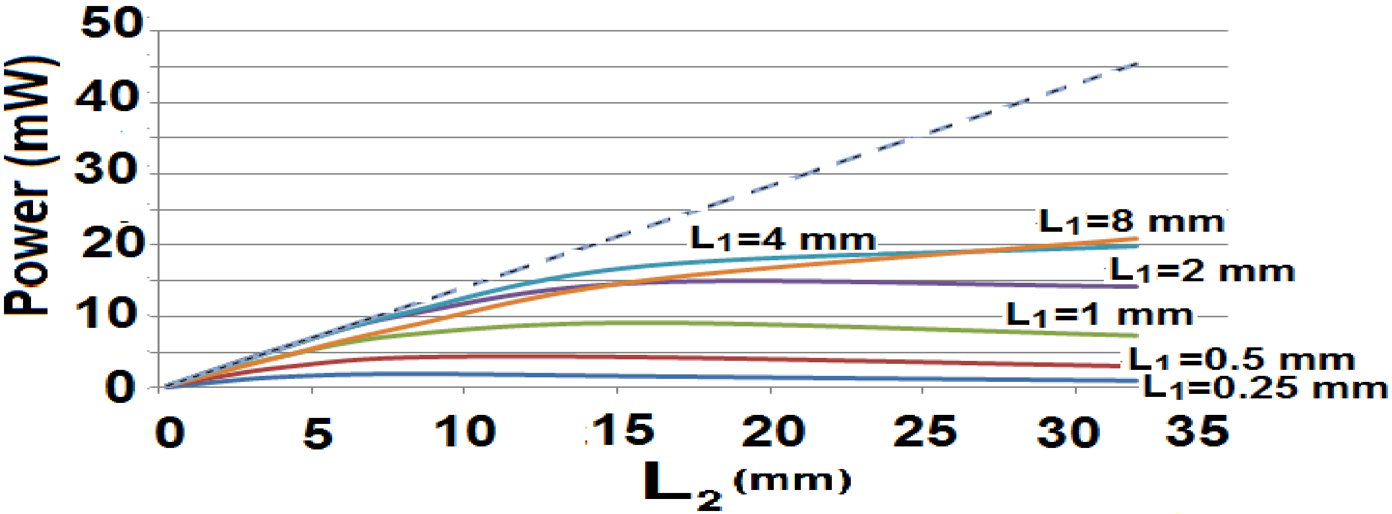


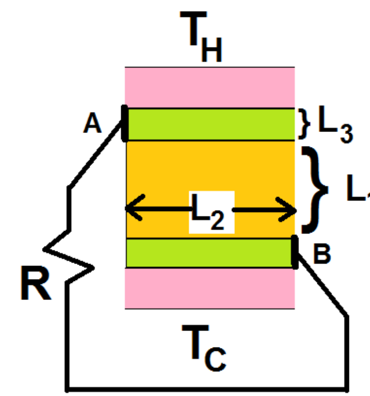


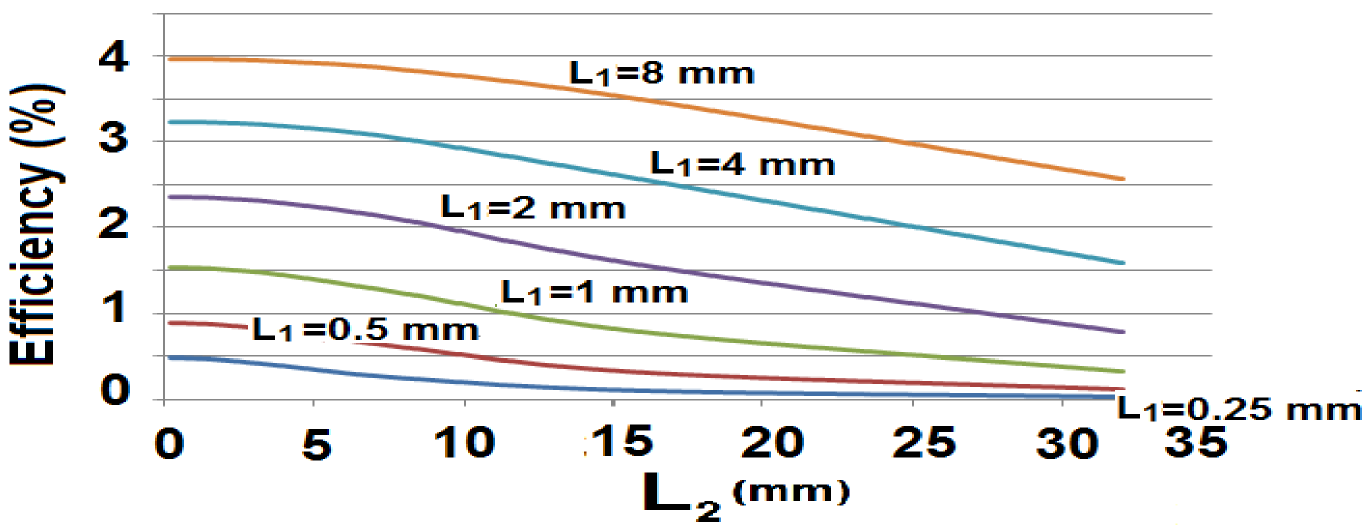
POWER INCREASES, THEN DECREASES WITH PELLET AREA.



POWER AND EFFICIENCY, VARYING L_1, L_3=0.1 mm



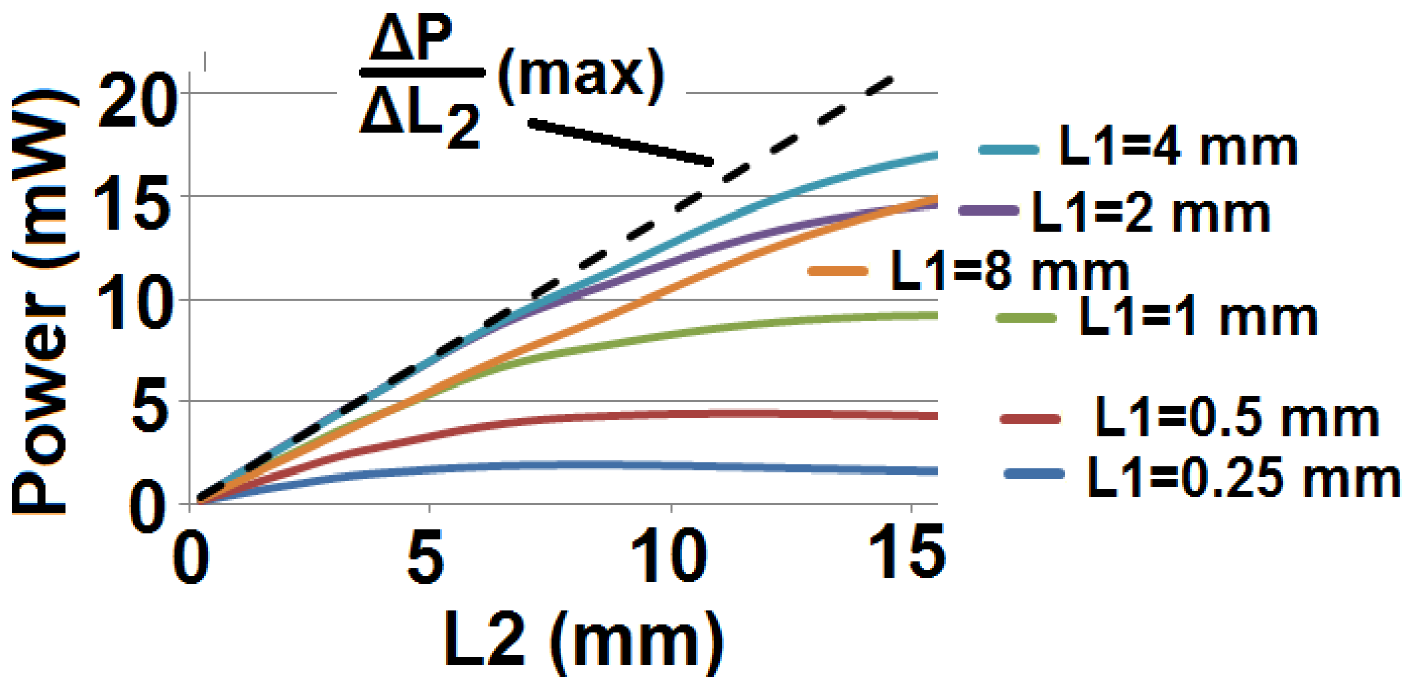




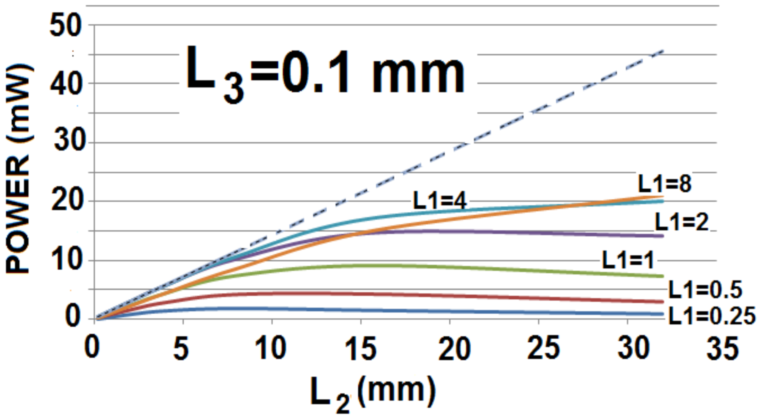
GRAPHICAL GUIDANCE FOR CHOOSING THERMOELEMENT HEIGHT L_1 AND LENGTH L_2

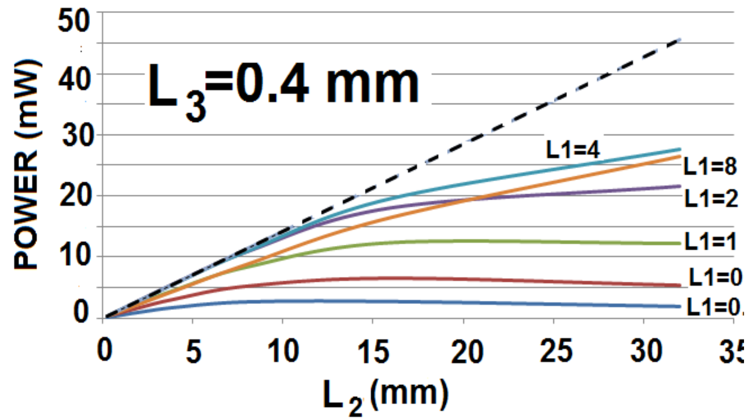
1. DETERMINE CURVE(S) HAVING HIGHEST POWER FOR SMALL L2. THIS YIELDS L1 CANDIDATES.
2. EXTRAPOLATE THE INITIAL SLOPE. THIS BRACKETS POWER INCREASES WITH L2.
3. AS POWER DEVIATES FROM IDEAL, DIMINISHING IMPROVEMENT WITH L2.

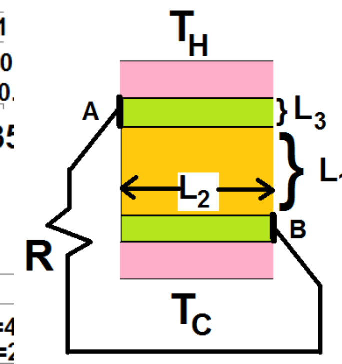
CONDUCTOR WIDTH L3=0.1 mm

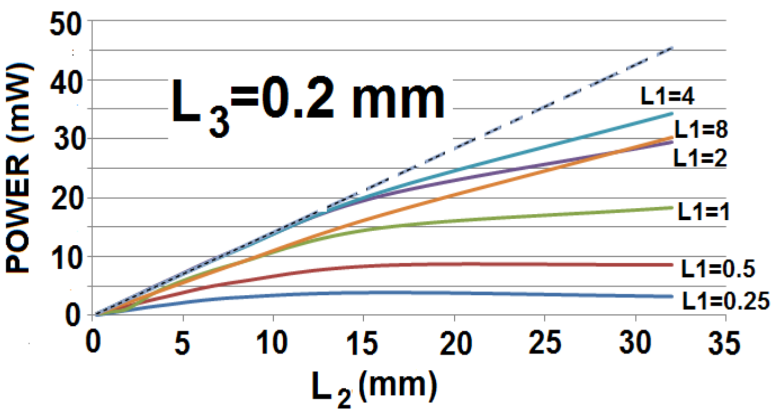


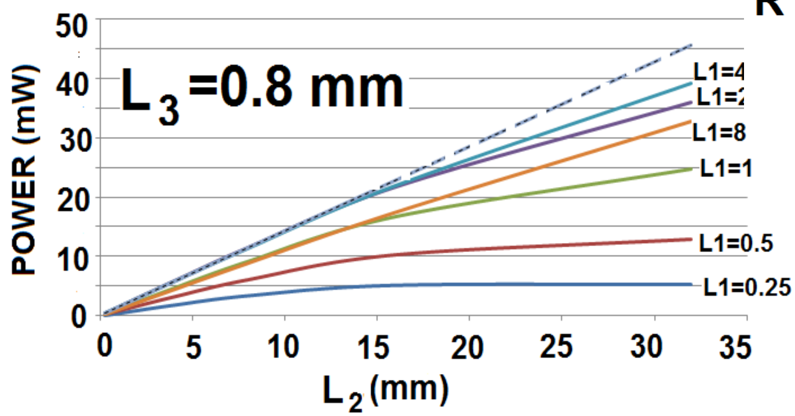
POWER GENERATION CHANGES WITH CONDUCTOR THICKNESS L_3



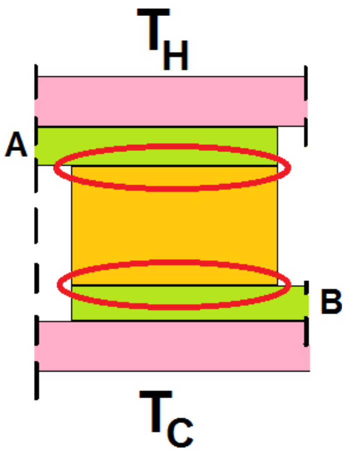






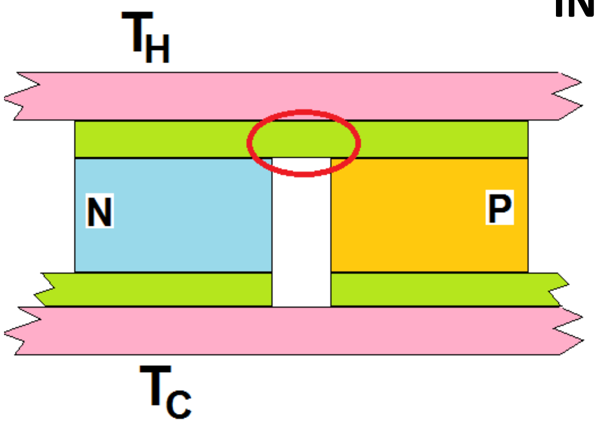


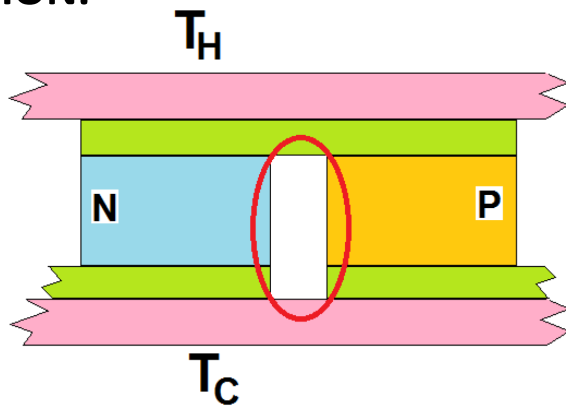
CONTACT RESISTANCE AND OVERHANG LOSS



CONTACT RESISTANCE ADDS TO ELECTRICAL PARASITICS. EFFECT CAN BE REDUCED BY INCREASING L1 DIMENSION*

OVERHANG IN THE ELECTRICAL CONNECTION BETWEEN THERMOELEMENTS INTRODUCES BOTH ELECTRICAL AND THERMAL PARASITICS. EFFECT CAN BE REDUCED BY INCREASING L2 DIMENSION.

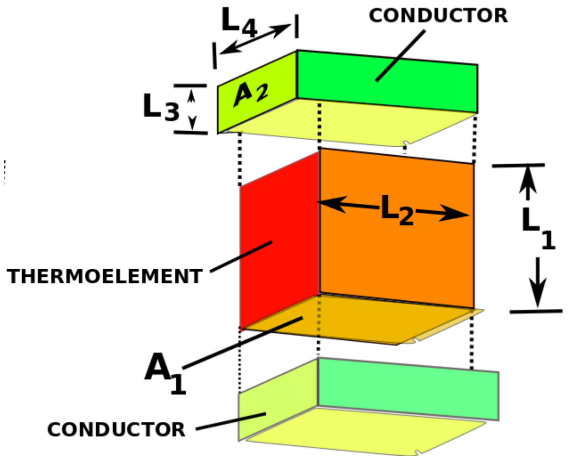




* D. Ebling, K. Bartholome, M. Bartel and M. Jagle, "Module geometry and contact resistance of thermoelectric generators analyzed by multiphysics simulation", **J. Electronic Materials**, (2010) 39: 1376-1380.

DESIGNING TO REDUCE PARASITICS

IF	THERMAL PARASITICS	ELECTRICAL PARASITICS
L1 INCREASES	DECREASE[1]	EITHER[2]
L2 INCREASES	DECREASE[3]	EITHER[4]
L3 INCREASES	INCREASE[5] (MARGINAL)	DECREASE



1 We get more temperature drop across the thermoelement

2 Desensitizes the effect of contact resistances (that's good). Increases electrical resistance (that's bad).

3 Proportional reduction in thermal leakage through overhang.

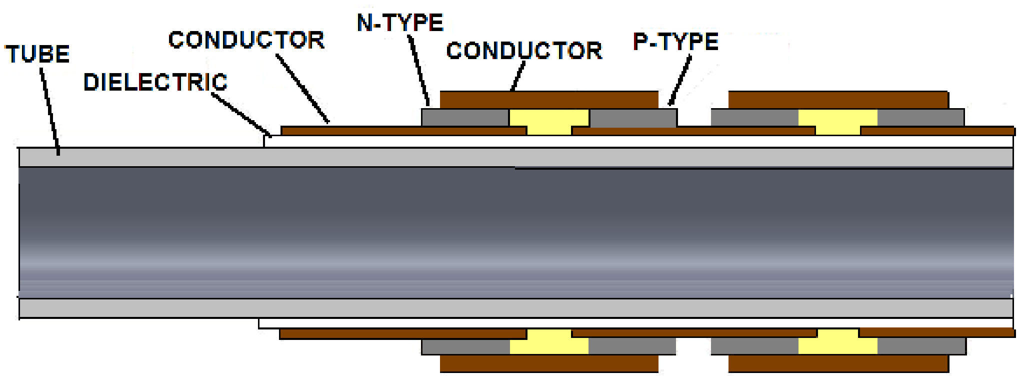
4 May reduce or increase internal electrical resistance. Will reduce influence of overhang resistance.

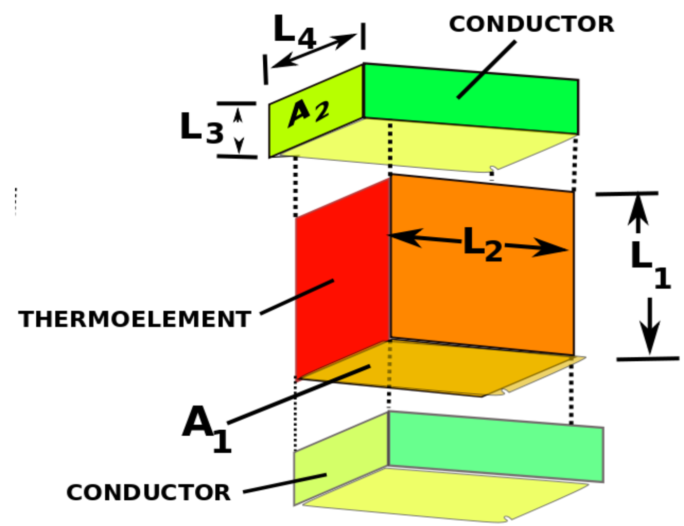
5 Causes some temperature drop but good electrical conductors are good thermal conductors so may be negligible.

OTHER FACTORS THAT IMPACT CHOICE OF THERMOELEMENT GEOMETRY

COST – THICK THERMOELEMENTS USE MORE MATERIAL.

HEAT EXCHANGE PERFORMANCE --- COATING HEAT EXCHANGER WALLS WITH THERMOELECTRIC GENERATION CIRCUITS INCREASES THERMAL RESISTANCE





SUMMARY

IT'S NOT ONLY ABOUT Z ---- σ, λ , S HAVE INDIVIDUAL IMPORTANCE AS DOES TOPOLOGY AND GEOMETRY. THE INFLUENCE OF PARASITICS MAY DICTATE THE BEST CHOICE OF THERMOELECTRIC

THE HIGHEST POWER DESIGN MAY NOT (USUALLY WON'T BE) THE HIGHEST EFFICIENCY DESIGN

IN A PI TOPOLOGY, THERMOELEMENT HEIGHT & LENGTH (L1 & L2) & CONDUCTOR HEIGHT L3 ARE ALL IMPORTANT TO MANAGING PARASITICS. THE DIMENSION PERPINDICULAR TO THERMAL AND ELECTRICAL CURRENTS (L4) IS FREE.

FOR A HEAT EXCHANGER APPLICATION, HEAT TRANSFER MAY DICTATE THINNER ELEMENTS.

ACKNOWLEDGEMENTS