Environmental Energy Harvesting Thermoelectric Power System

presented at the

Energy Harvesting Program Review

DARPA Advanced Energy Technologies

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by

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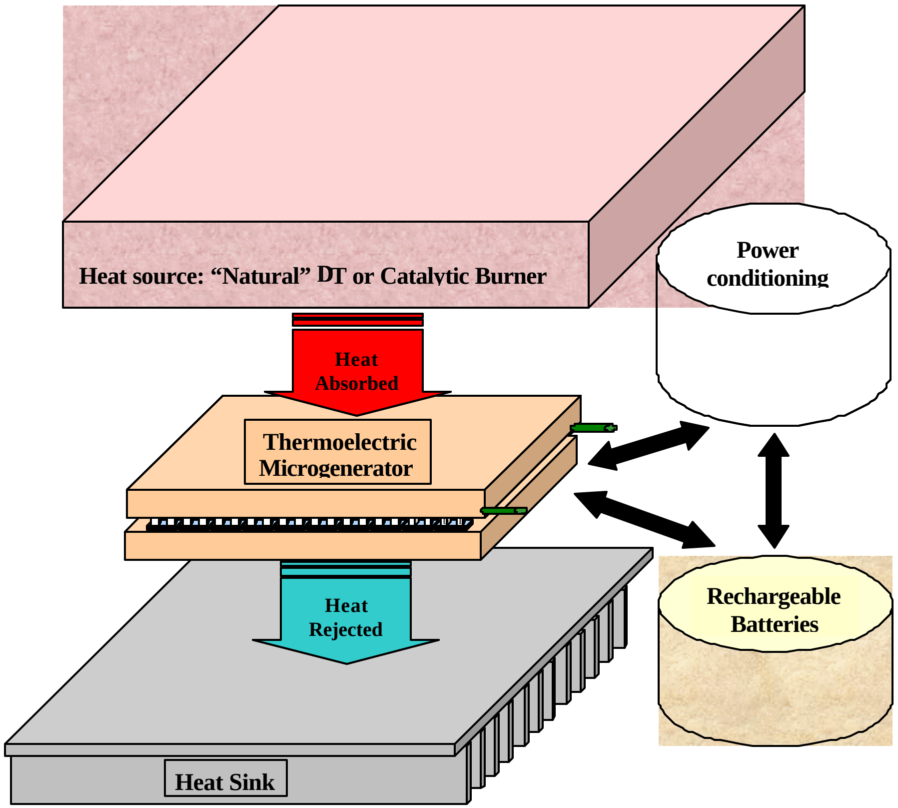
Thermoelectric Power System

- DARPA-sponsored effort: thermoelectric microdevice integration into a compact, versatile power source
  - **3-year program**
  - **JPL / US CECOM Team**
  - **For terrestrial applications**
- Integrated power source
  - **Heat source/delivery**
  - **Thermal-to-electric converter**
  - **Heat sink/radiator**
  - **Energy storage**
  - **Conditioning electronics**
- Design specifications
  - **10-600 mW output power**
  - **2-200°C DT across device**
  - **cross section ~ cm^2**
  - **Voltage and current compatible with rechargeable batteries**

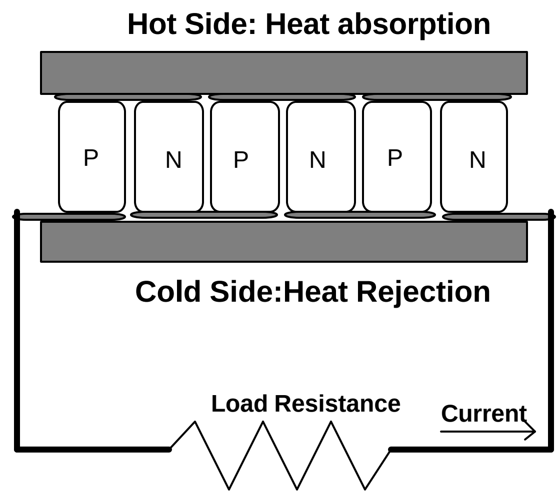


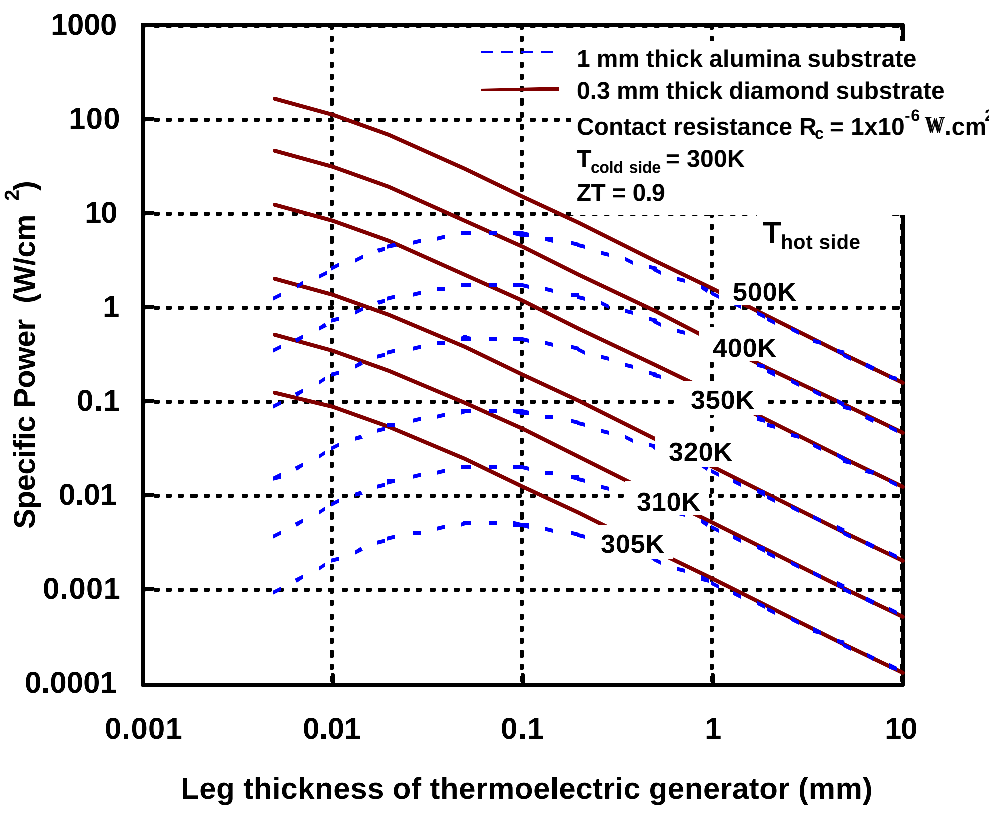
Key Challenges

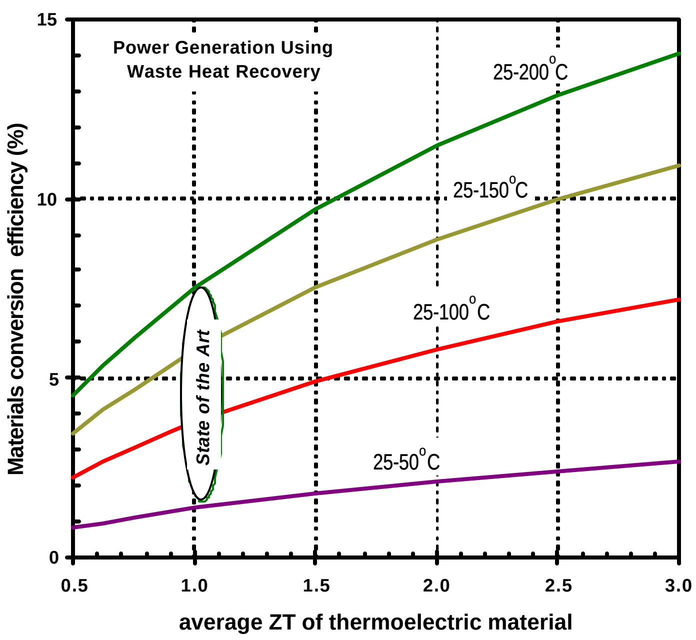
- Three year program
  - **3 main tasks**
    - **Thermoelectric microgenerator**
      - **J.-P. Fleurial (Task Lead)**
      - **G. J. Snyder**
      - **C.-K.o Huang**
    - **Heat sources, thermal modeling**
      - **S.R. Narayanan**
      - **P. Shakkottai**
    - **Power conditioning, rechargeable batteries**
      - **Ed Plichta (U.S. CECOM)**
      - **Mary Hendrickson (U.S. CECOM)**
- Major technical challenges
  - **Microgenerator development**
  - **Miniature catalytic burner**
  - **Device integration**
- Risk mitigation
  - **Bulk miniature thermoelectric modules are backup (developed in JPL/NASA/DOE program)**
    - **High aspect ratio, low heat flux device**

Predicted Performance of Miniature Thermoelectric Power Sources

Key challenges:
Device design and integration for optimum heat transfer and temperature differentials







TEMG: Possible Configurations

Power Source (W)	0.1	0.1	5	5	5
Duty cycle	1%	10%	1%	1%	10%
TEG output (mW)	11	13.5	59	66	590
Legs d x h (µm)	28x50	56x50	56x20	13x40	34x40
Number of couples	8000	4000	8000	4000	2000
Device area (cm^2)	0.25	0.5	1.0	0.5	0.15
Heat input (W)	1.1	5.6	27.0	13.9	8.4
ΔT (K)	2	5	5	10	200
Current (mA)	0.34	3.4	7.6	8.3	7.5
Voltage (V)	3.2	3.9	7.8	7.9	79
Efficiency (%)	0.10	0.25	0.22	0.47	7.03

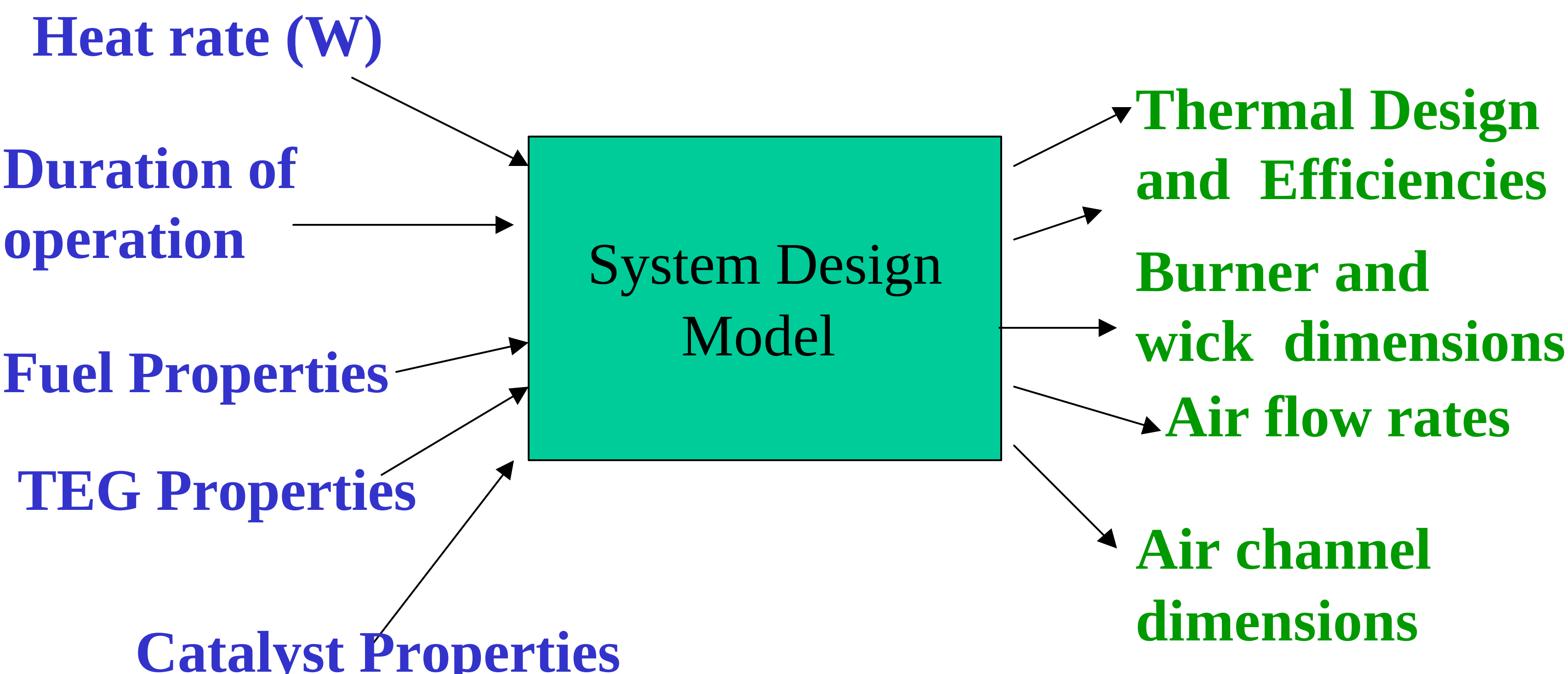
Catalytic Burner Task Technical Challenges

- Miniaturization of system: compact power source <100 cm^3
  - **Develop model for heat generation and heat collection**
    - **Methods of efficient heat transfer, optimization of fuel delivery rates**
  - **Integrate thermal source model with TEG model**
- Fuels
  - **Logistic fuels: JP4, Diesel, Gasoline**
  - **Available from the environment: Methane, methanol, ethanol, formic acid**
  - **Key advantage of liquid fuel arises from self-adjusting temperature property**
    - **Gaseous fuels can result in temperature overshoot**
    - **Gaseous fuels are easy to deliver, liquids need to be wicked or pumped**
      - **But storage of gaseous fuel inefficient compared to liquids.**
- Catalysts
  - **Activity for oxidation must be high (Low initiation temperature)**
  - **Operating temperature must allow operating TEMG hot side at < 250^{o}C**
    - **Low to medium combustion temperatures 200-500^{o}C.**
      - **Hydrocarbons (300-600^{o}C), alcohols (150-300^{o}C)**
  - **Catalyst dispersion must be high and catalyst must resist poisoning**
    - **Catalyst/supports must be stable at operating temperatures**
      - **Zeolite, AlN - catalyst nanoparticles**

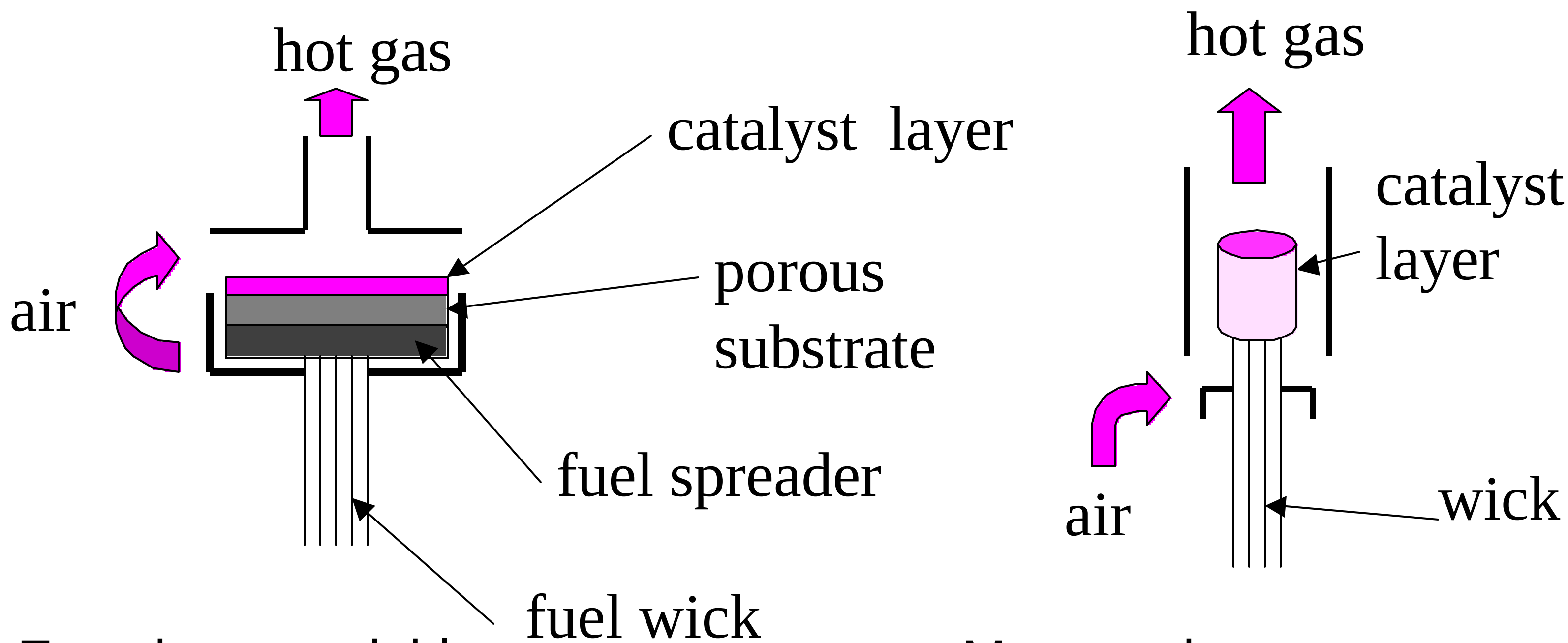
Catalytic Burner Development

- Preliminary Burner Design Studies
  - **To verify fundamental operational modes**
    - **Design and demonstrate operation in prototypes**
  - **Materials selection and burner architecture**
    - **Temperature measurements and sensitivity studies**

INPUTS **OUTPUTS**

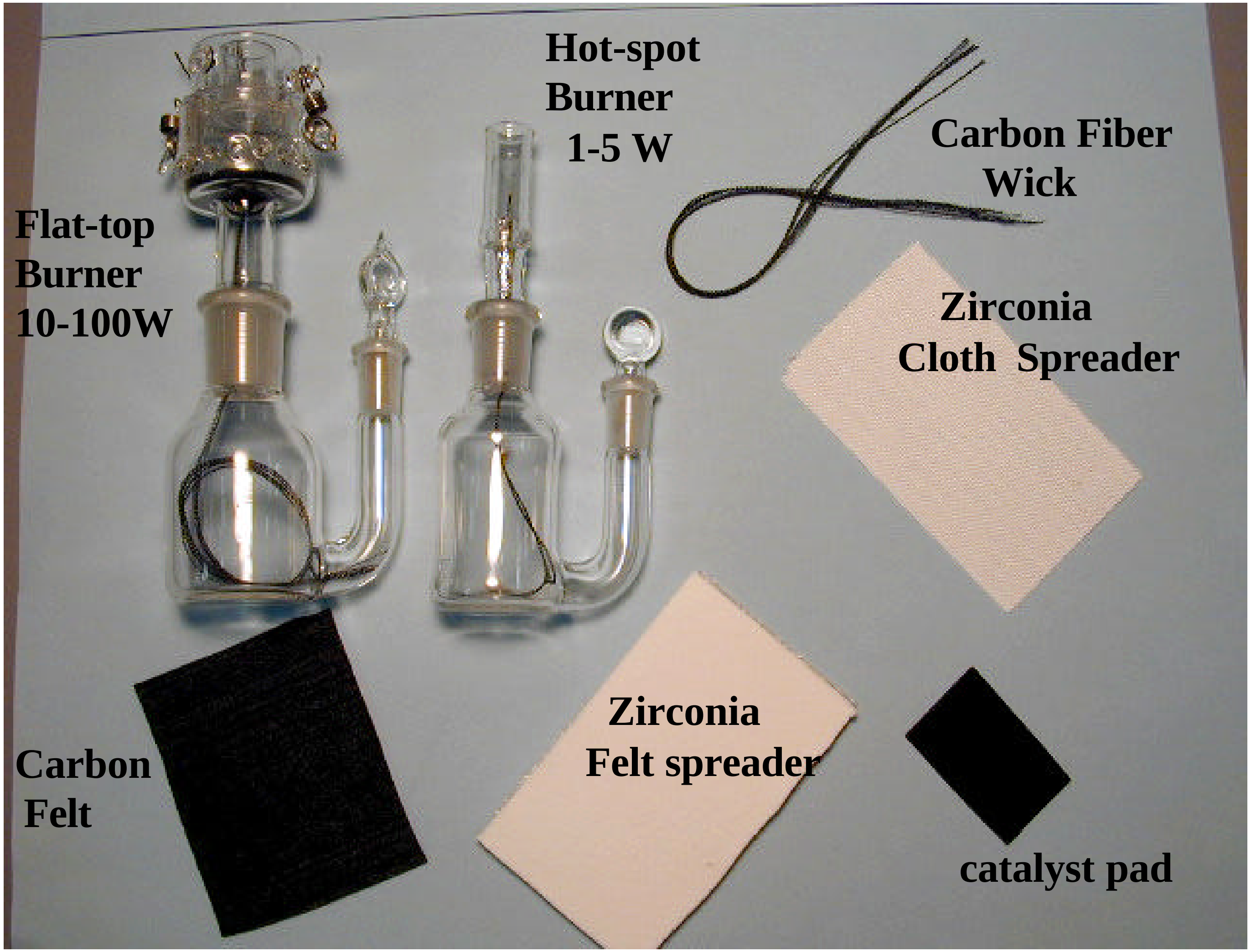


Schematic of burner configurations used in design studies



- Experiment variables
  - **number of wicking elements**
  - **Amount of catalyst**
  - **Area of burning surface**
  - **Amount of air access**
  - **Materials**
- Measured outputs
  - **Surface temperature**
  - **Hot gas temperature**
  - **Wicking rates**
  - **Material stability**

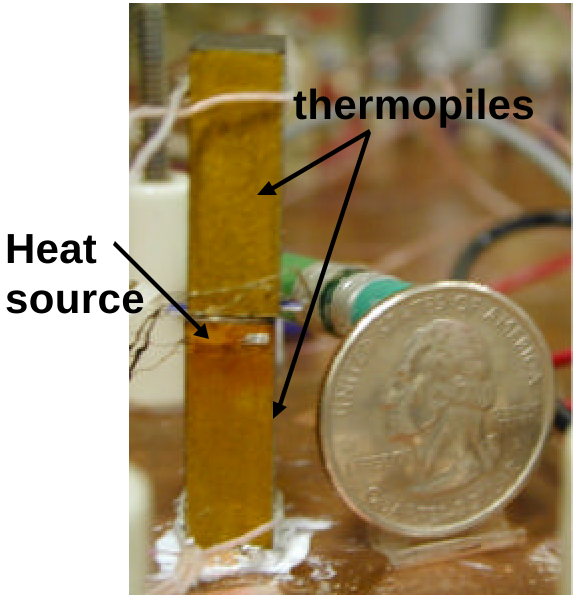
Burners used in Preliminary Design Studies

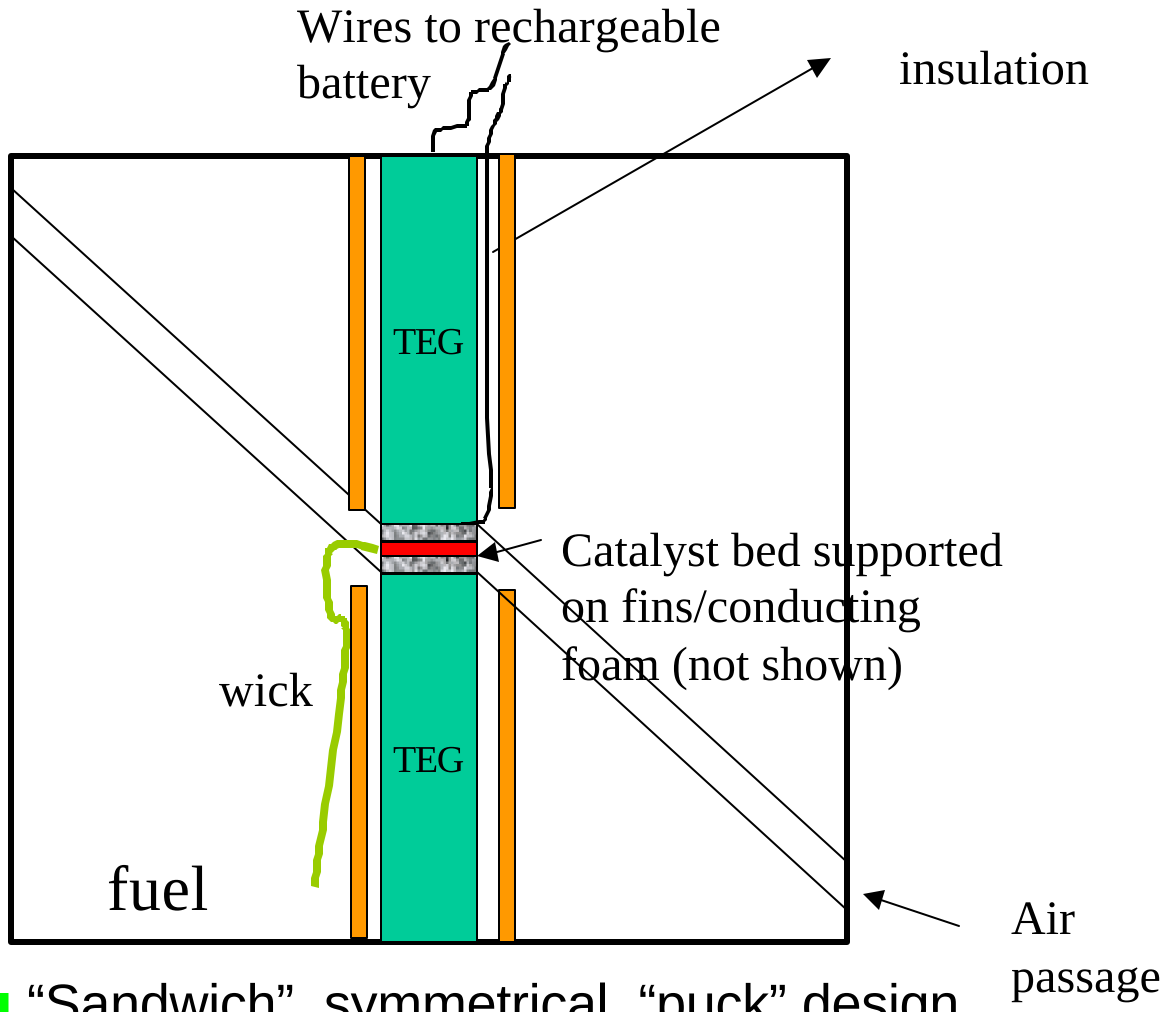


Results of Preliminary Burner Studies

- Methanol burners were self-starting, requiring no pre-heat
  - **Wicking rate can be determined by choosing appropriate number of wick elements.**
- Surface temperature as high as 450^{o}C can be attained.
  - **Surface and hot gas temperature were a strong function of air flow rate**
  - **Natural convection was sufficient to sustain thermal output of 10-20 W/cm^2 of burner surface**
    - **Could be used with various thermoelectric converter design**
- Catalyst activity adequate for present applications
  - **Plain platinum black catalyst undergoes sintering at high temperatures**
  - **Can be avoided by supported catalysts (Pt/Al_2O_3)**
- Burners were operated for up to seven days continuously at 5-10 W
  - **Demonstrated steady-state operation**
  - **On/off operation may require preheating of the catalyst**
    - **Depends on choice of catalyst material and/or fuel**

Catalytic Burner/Bulk Thermopiles Preliminary System Design



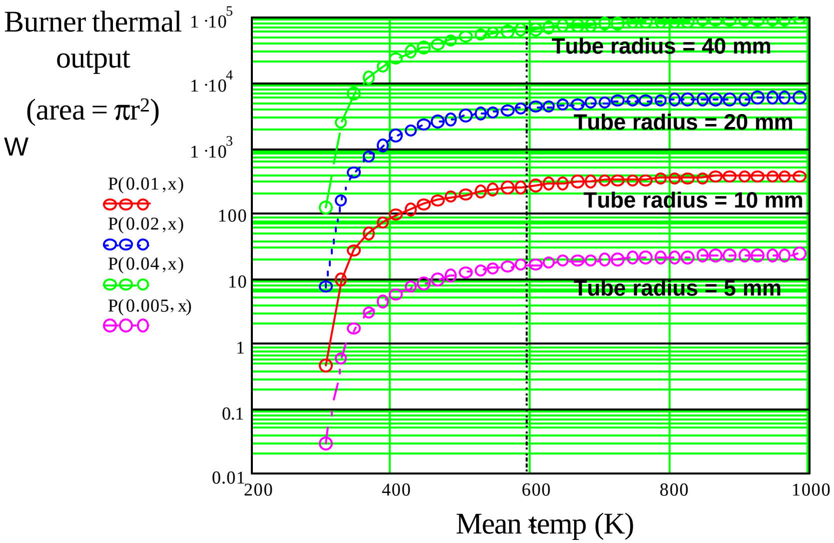


- "Sandwich", symmetrical, "puck" design
  - **Two bulk thermopiles, catalytic burner**
    - **Obtained from Ukrainian company (JPL/NASA/DOE Program)**

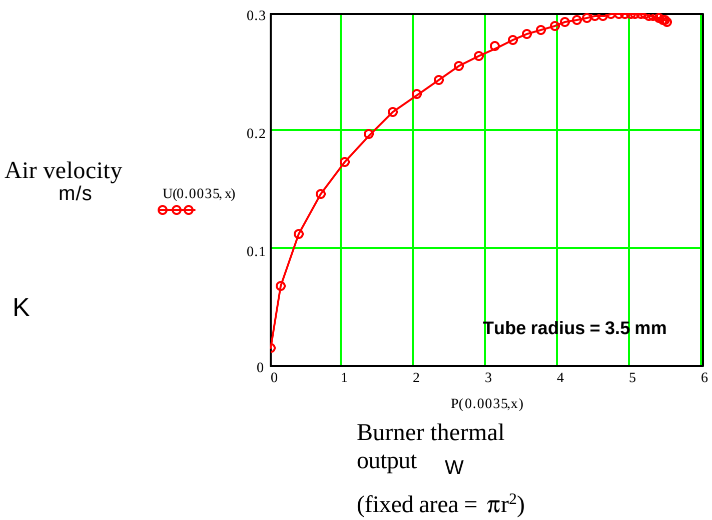
Results of Thermal Modeling Studies

- Model based on "natural" buoyancy effects
  - **Balance of buoyancy and frictional pressure drop determines power**
    - **Adjustment for chimney orientation must also be taken into account**
  - **Allows determination of burner design parameters and matching with requirements for thermoelectric converter**
    - **Self-consistent model, autoregulation of air/fuel mix**

Tubular Chimney with no fins: power, flow and temperature : 7mm d



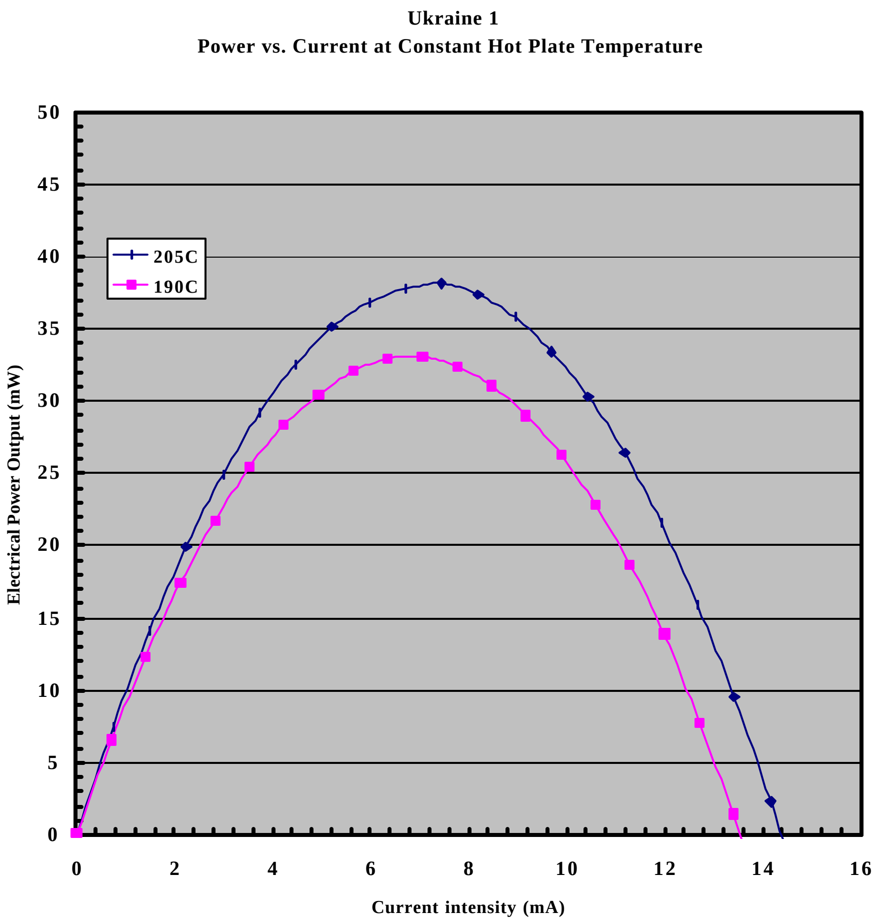
4th power dependance on radius is seen here. Bigger sizes can handle much more power.

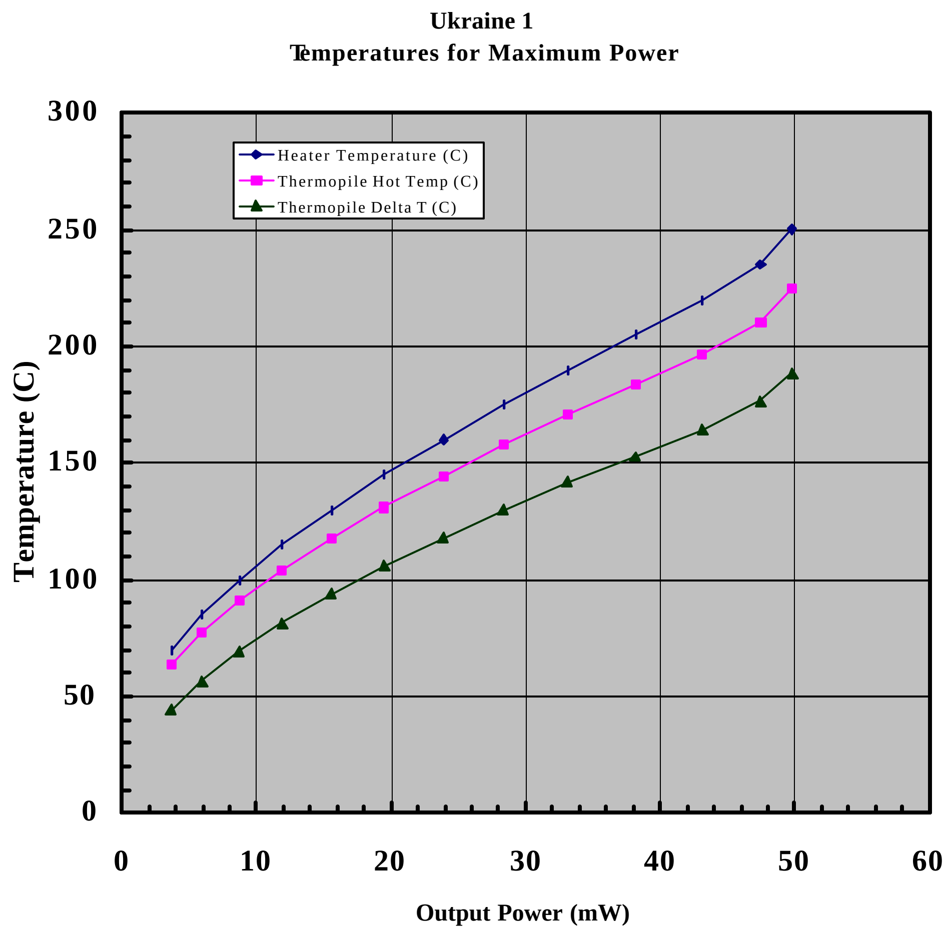


Velocity increases first and at high powers falls because of increased viscosity. Diameter of pipe is 7 mm.

Bulk Thermopile Performance

California Institute of Technology





- Thermopiles are 23mm long and 8x8 mm cross-section
  - **About 6.5% thermopile conversion efficiency with T_{hot} = 200ºC**
  - **40mW, 5V, 8mA electrical output under load (per thermopile)**

Design Estimates for 5 W device

- Sytem performance calculations for miniature bulk thermopiles
  - **Includes mass estimate for power conditioning electronics, rechargeable batteries, container**
  - **1.6% duty cycle projection (for illustration purpose)**
    - **10s on (5W), 625s off (recharge)**