

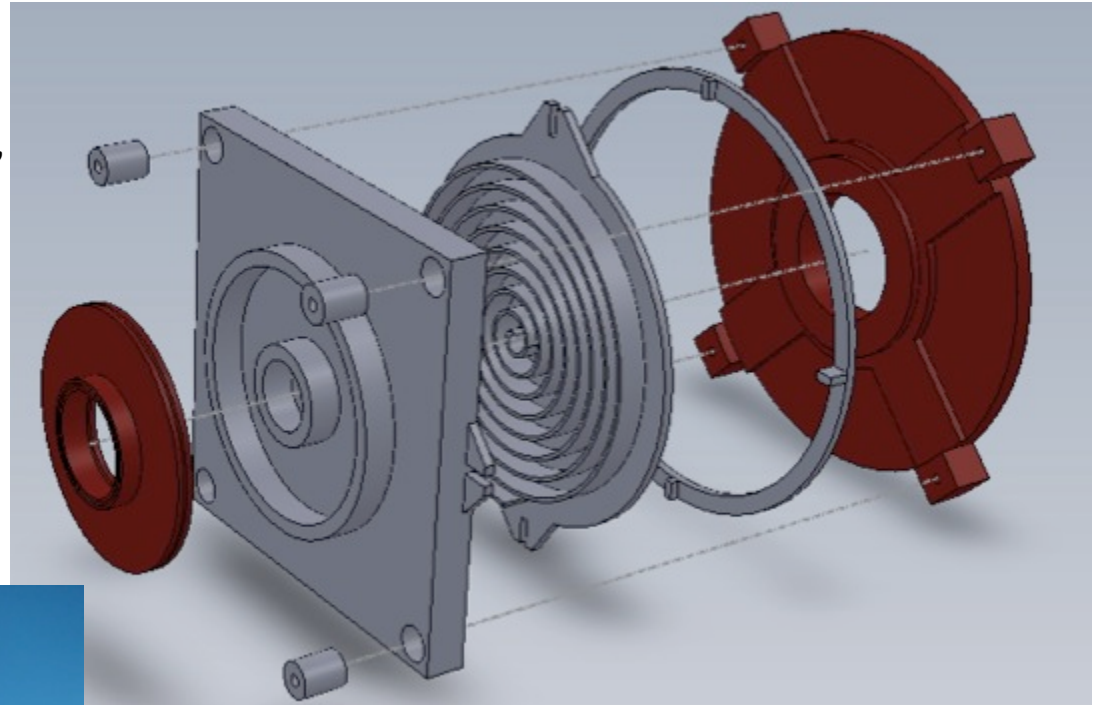
COMPARISON OF SCROLL AND PISTON EXPANDERS FOR SMALL SCALE ORC APPLICATIONS



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Why Solar?

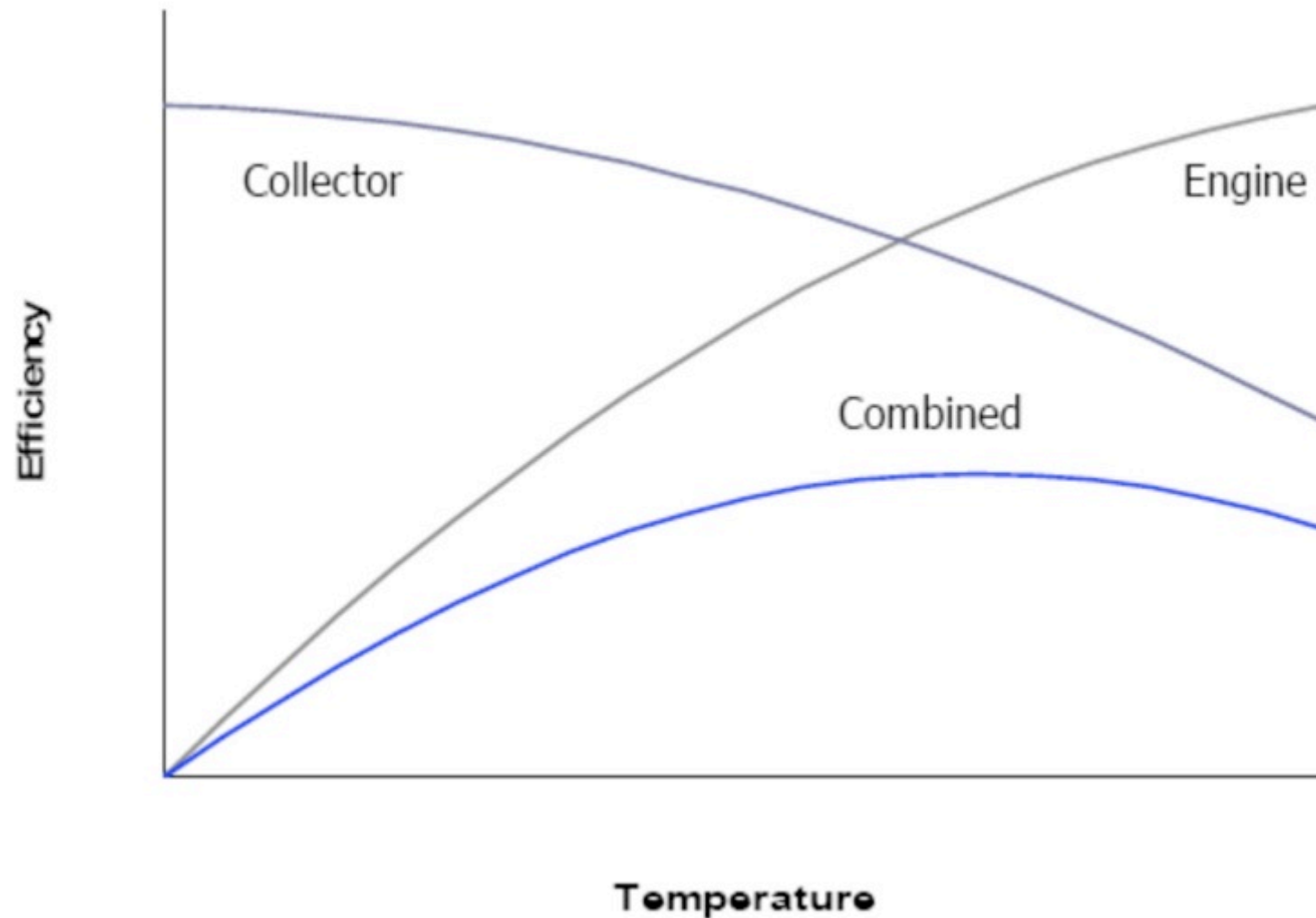


Why ORC?

1.5 Billion 



Collector absorption (vs. radiation and conduction) losses diminishes at higher temperature; Engine thermodynamic efficiency increases with higher temperature



Referencing thermodynamic to economic factors indicates ~135°C operation

Motivation



Solar thermal + ORC

Well proven at MW scale

LCOE ~ \$0.20/kWh

Not available at smaller scale

Small scale



Distributed applications

On-site cogeneration

Renewable

Local manufacture and
maintenance

Competing Technologies: 25kWh/day



**3kW STG
Solar ORC**



4kW PV



1.2 kW Diesel

	3kW STG Solar ORC	4kW PV	1.2 kW Diesel
\$/kWh (LCOE)	0.30	0.32	0.50
\$/W capital cost	11	10	0.2
efficiency	8%	14%	25%
capacity factor	0.33	0.25	0.90
cogeneration	YES	NO	NO
CO ₂ emissions	NO	NO	YES

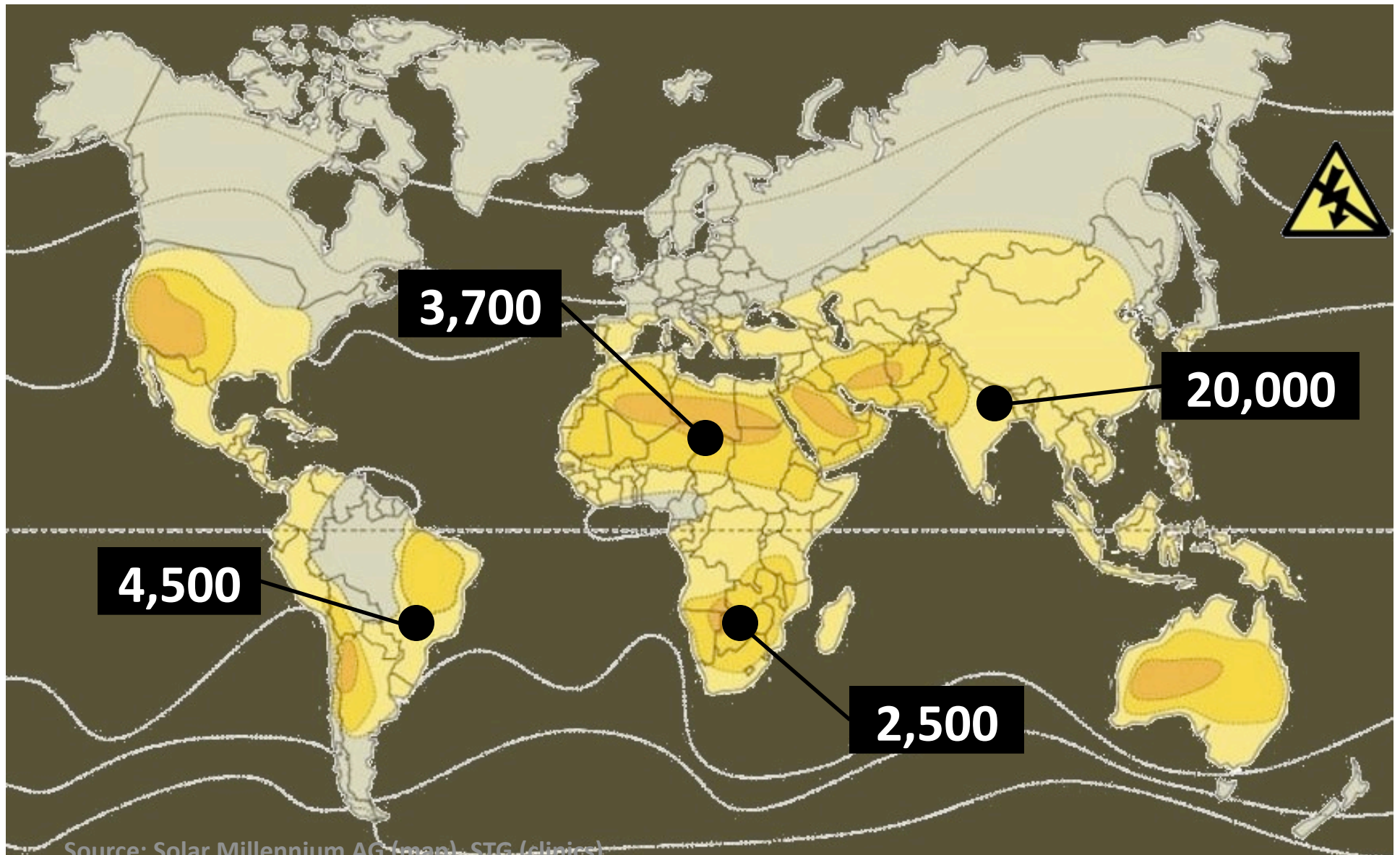
Remote Health Clinics

5-30 kWh/day

Need for hot water



Number of Unelectrified Rural Clinics - solar resource map



Rural School Electrification

India and China	25,000
Sub-Saharan Africa	15,000
South America	8,000
Southeast Asia	8,000



Other applications

Tribal reservations



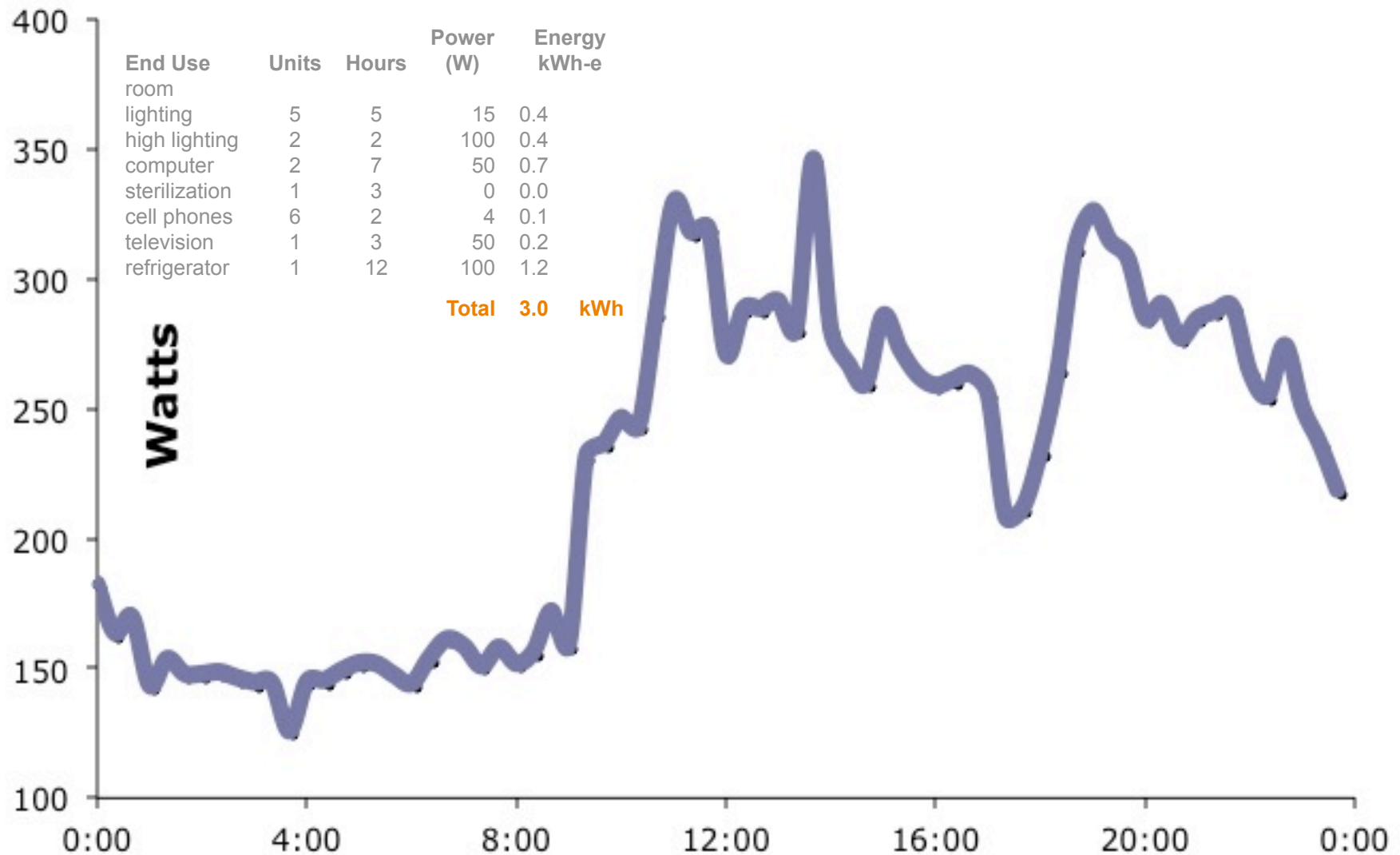
Reconstruction and development



Remote water purification and pumping

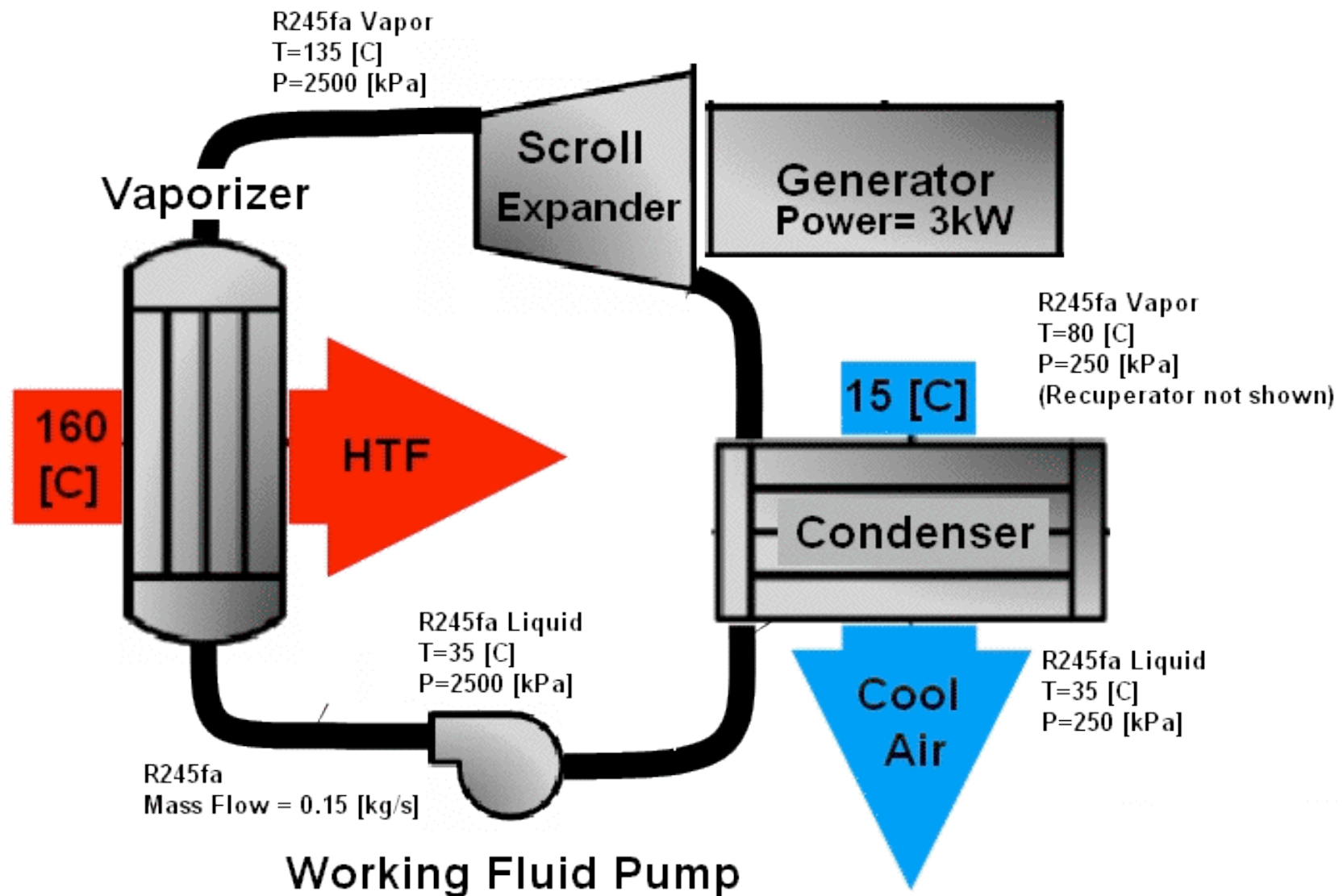


PIH Clinic Load Curve Weekday 5.5 kWh/day



ORC Power Spec: 3 kW electricity for ~ 6.5 hours = 20 kWh per day

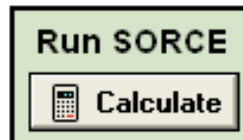
Organic Rankine Cycle



Solar Organic Rankine Cycle Economic (SORCE) Model

Matthew Orosz July 2010

To access model parameters, click on the modules below



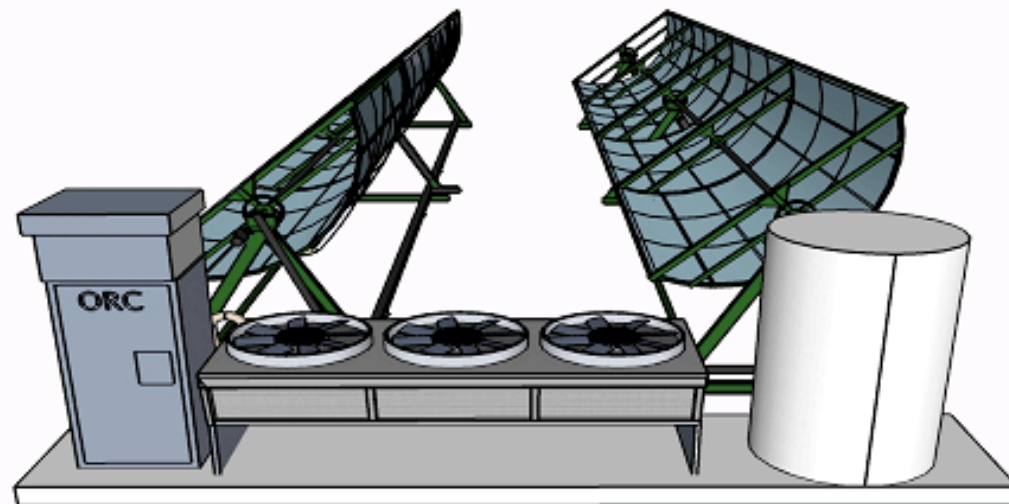
Solar
Resource

Solar
Collector

Thermal
Storage

ORC

Economics



Calculated Output

Hour_{AVE} = 9.564

$I_{\text{beam}} = 745.3 \text{ [W/m}^2\text{]}$

Solar_{Input} = 85.71 [kW]

Thermal_{Power} = 49.24 [kW]

$\eta_{\text{Col}} = 57.44 \text{ [\%]}$

$\eta_{\text{cycle}} = 5.781 \text{ [\%]}$

$P_{\text{net}} = 2.879 \text{ [kW]}$

Power_{day} = 27.54 [kWh]

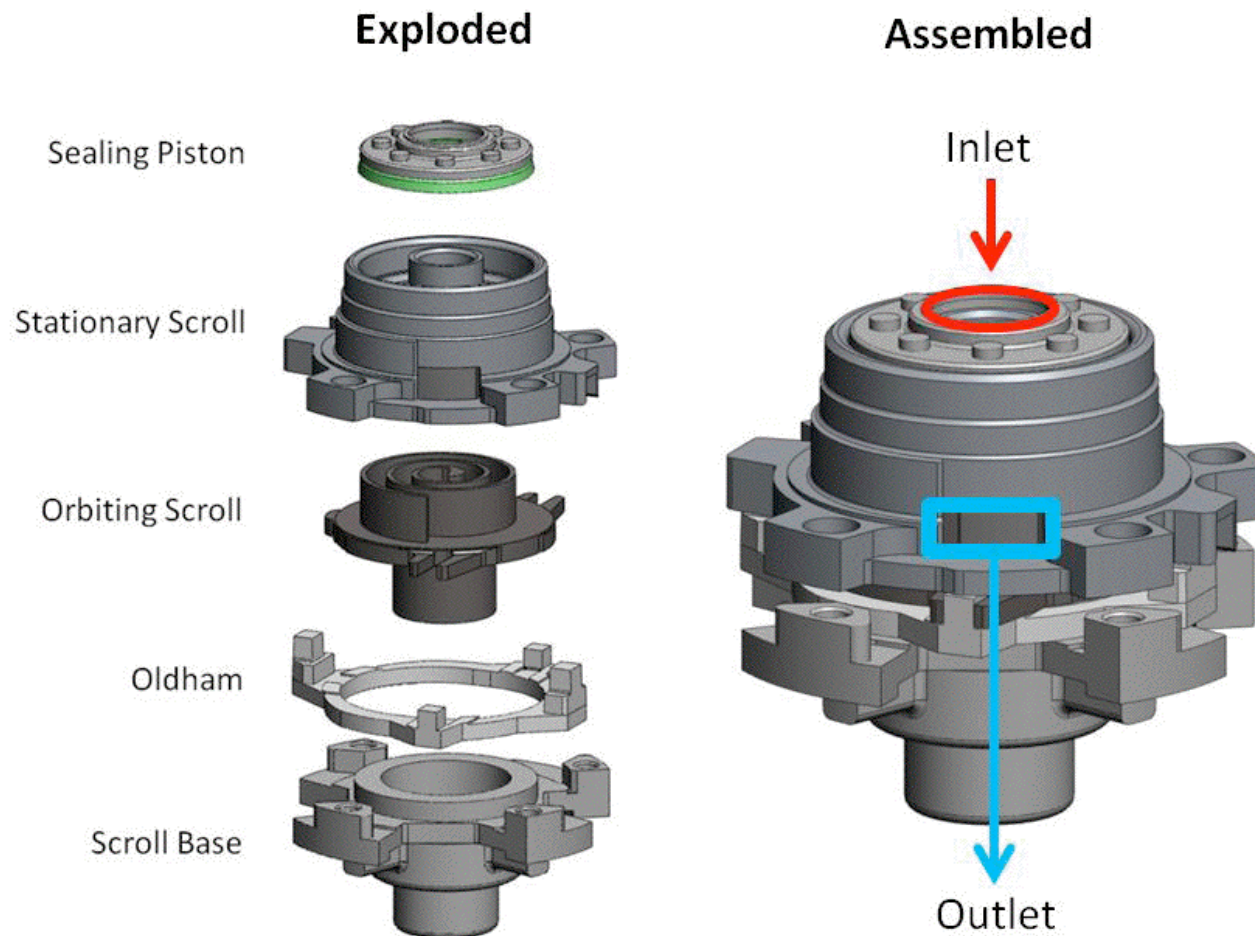
LCOE = 0.2775 [\$/kWh]

Cost_{Tot} = 41841 [\$]

<http://web.mit.edu/mso/www/SORCE.exe>

Adapting a scroll compressor for expander mode:

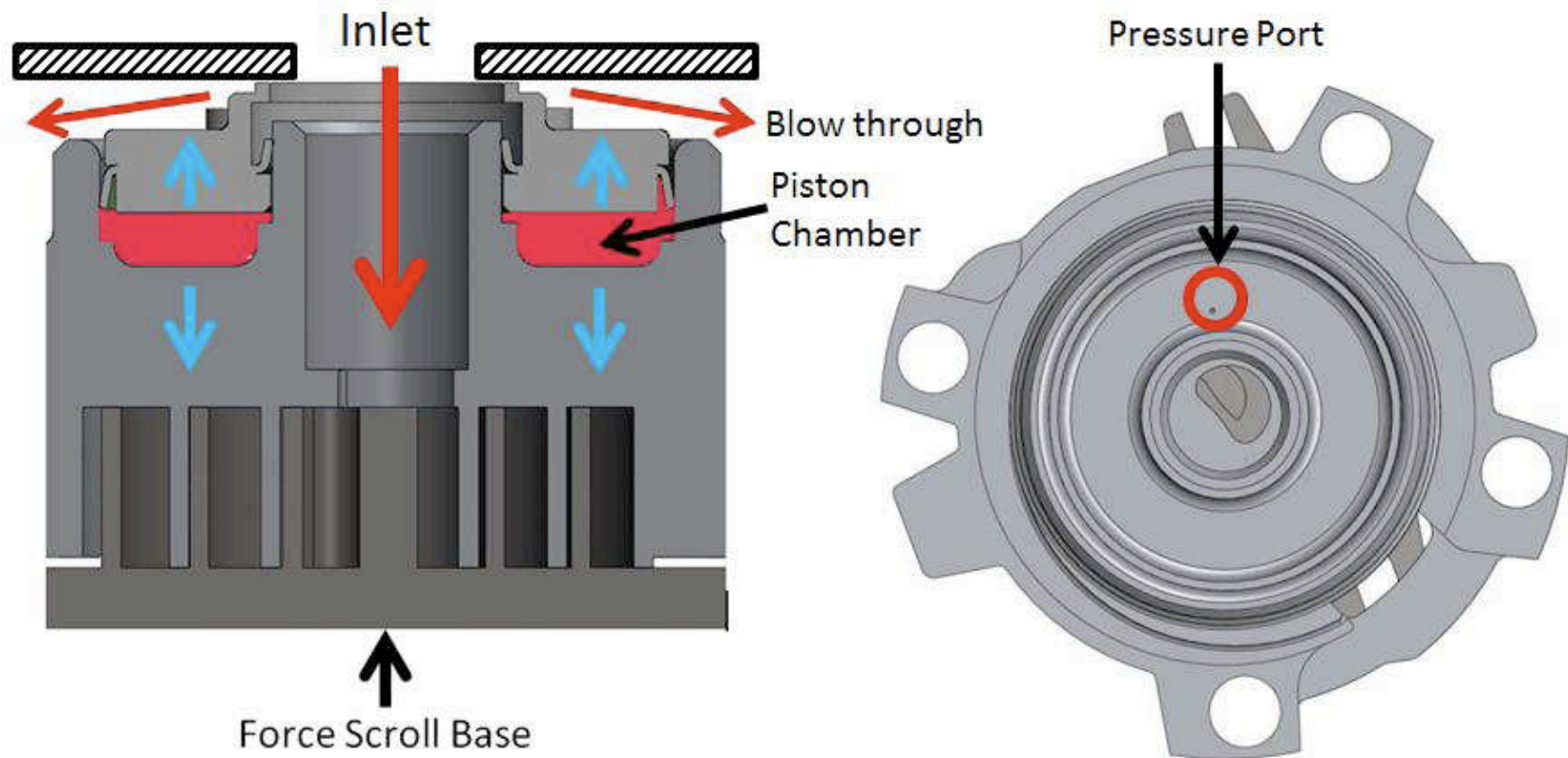
First open up the can and see what is inside.



Source: Harada 2010 Development of a Small Scale Scroll Expander.

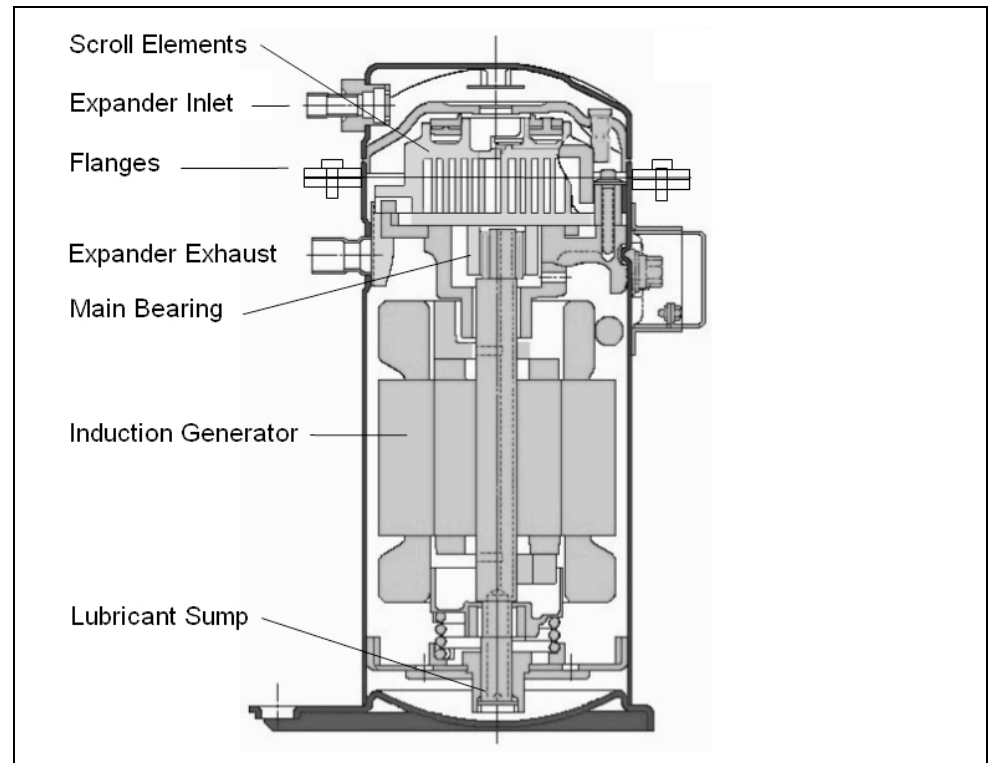
Adapting a scroll compressor for expander mode:

- 1) Remove check valves and bypass valves
- 2) Optimize pressure port and support sealing piston with springs
- 3) Install Union ports
- 4) Install flanges to reseal the can



Source: Harada 2010 Development of a Small Scale Scroll Expander.

Adapted compressor expander

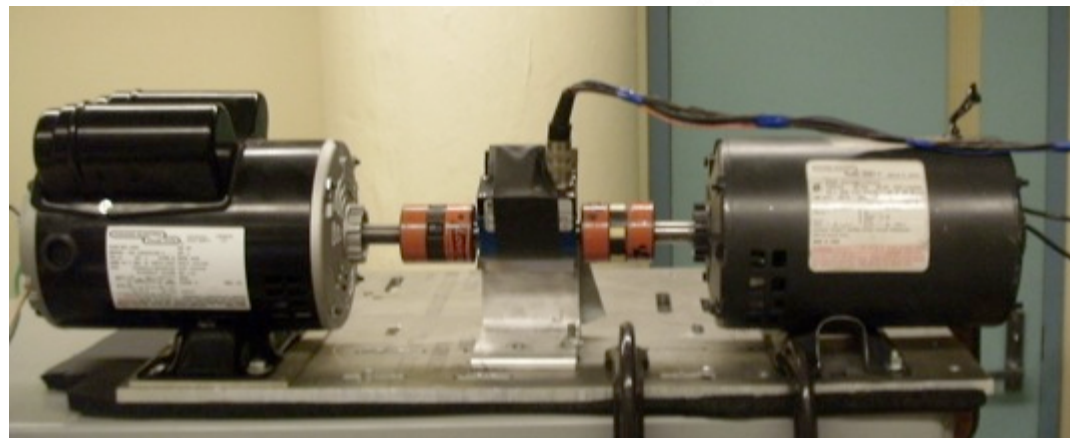
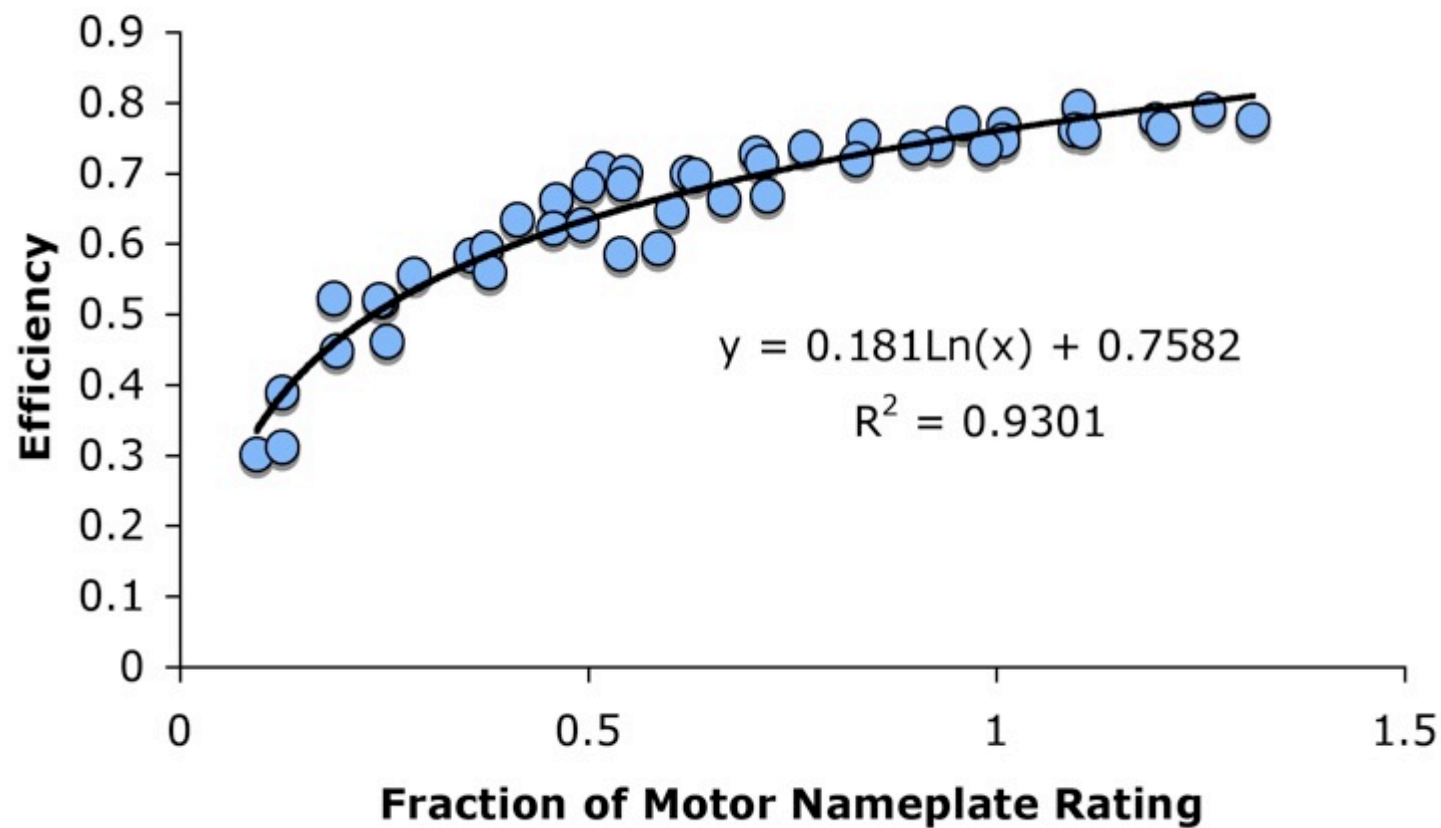


Benchmarking – The isentropic efficiency is unknown, so empirical determination is necessary to predict performance and size the unit.

MIT and U.Liege benchmarked several types of compressors

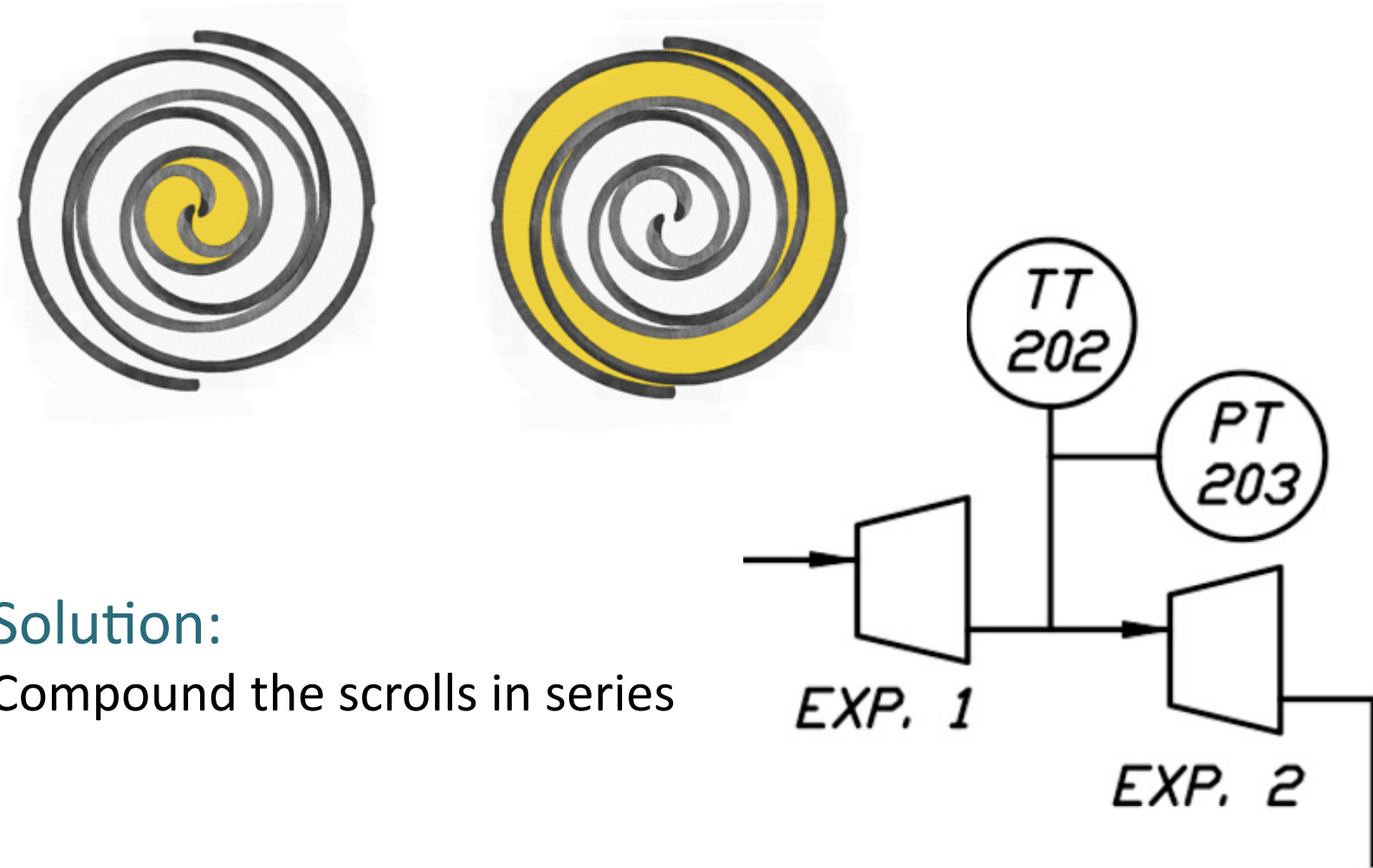
Generally, scroll machines are high efficiency, and available in range of displacements

Induction Generator Normalized Efficiency Curve



Intrinsic volume ratio of HVAC scrolls is low ~ 3

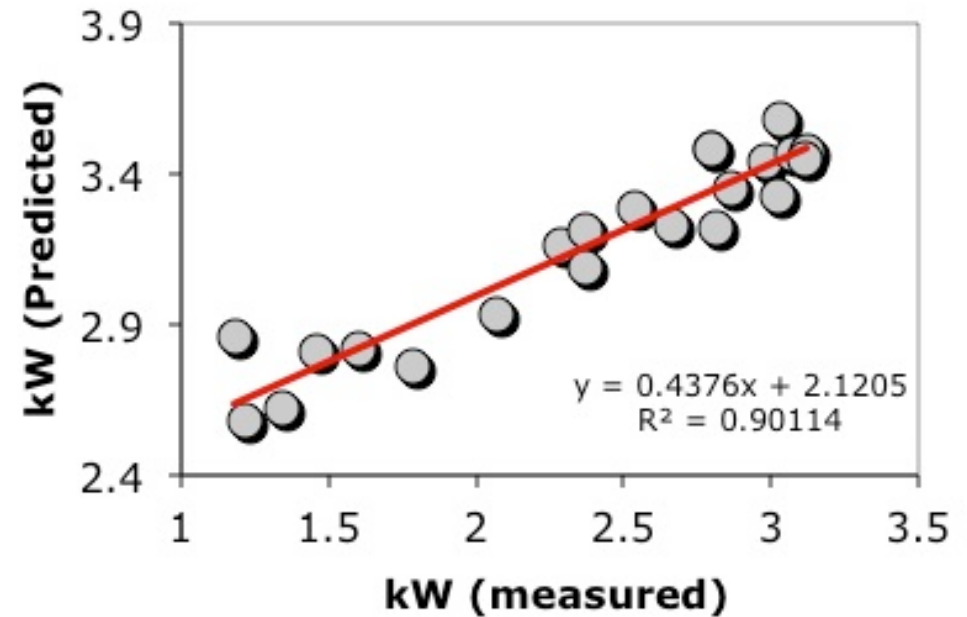
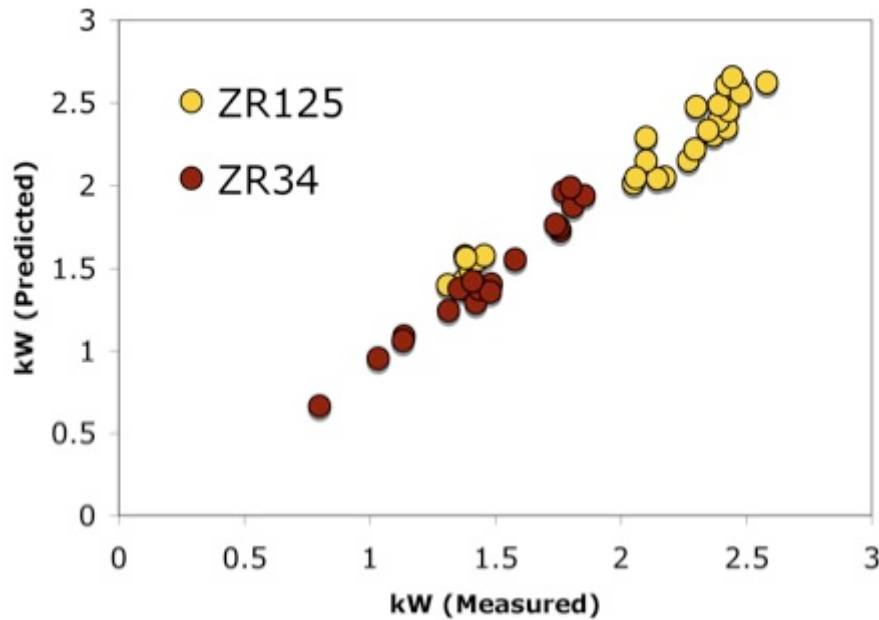
Ideal VR in an ORC at 135°C is usually >10 (depending on fluid)



Solution:

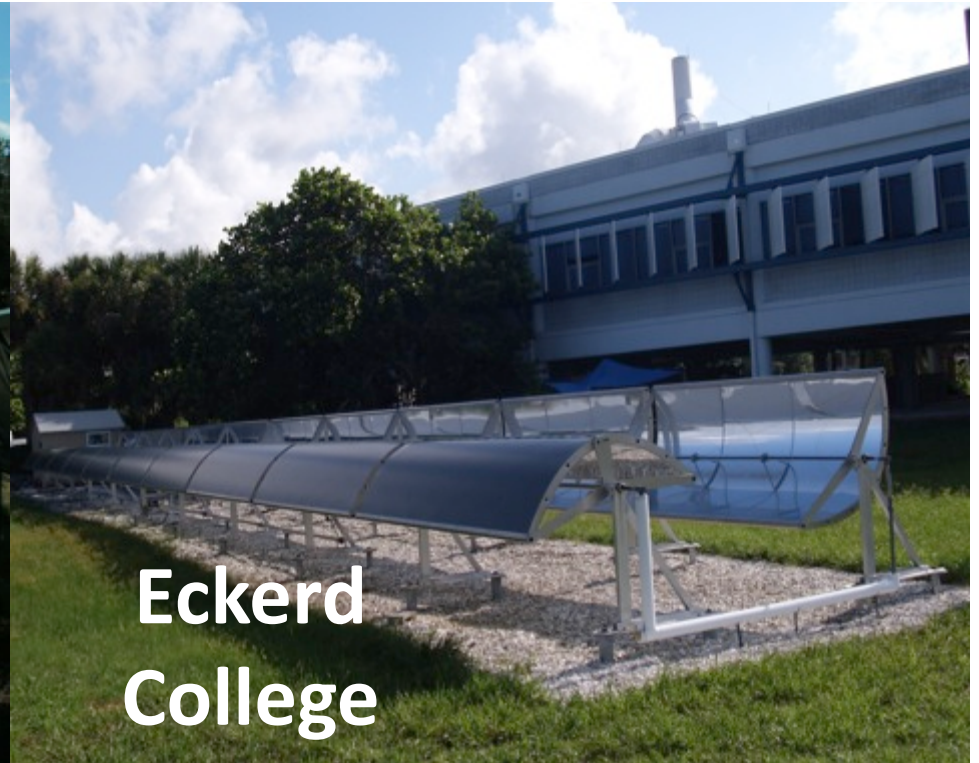
Compound the scrolls in series

Matched HVAC scroll expanders in 1stage and 2stage



Power output as predicted by SORCE and measured on the ORC test rig. An empirical isentropic efficiency coefficient of 0.815 for the Copeland ZR series was found by minimization of the variance ($R^2=0.96$) between predicted and measured power under various operating regimes. The coefficient includes the generator derating function.

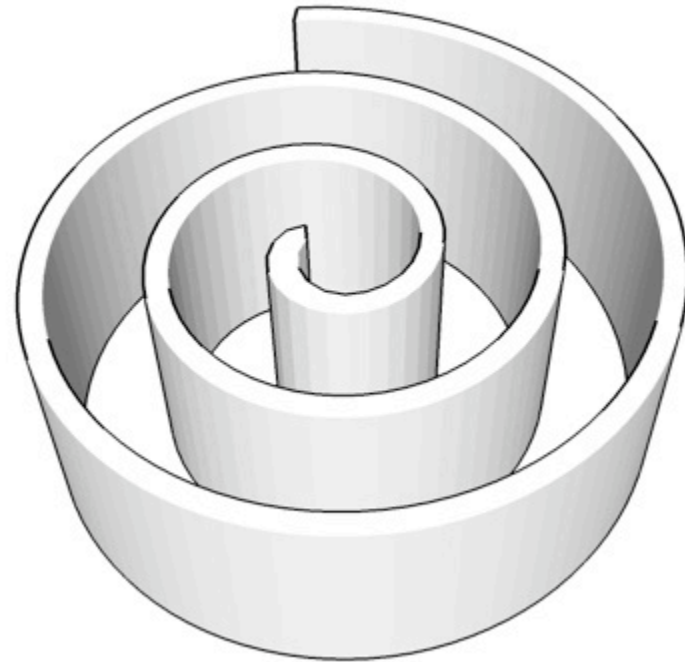
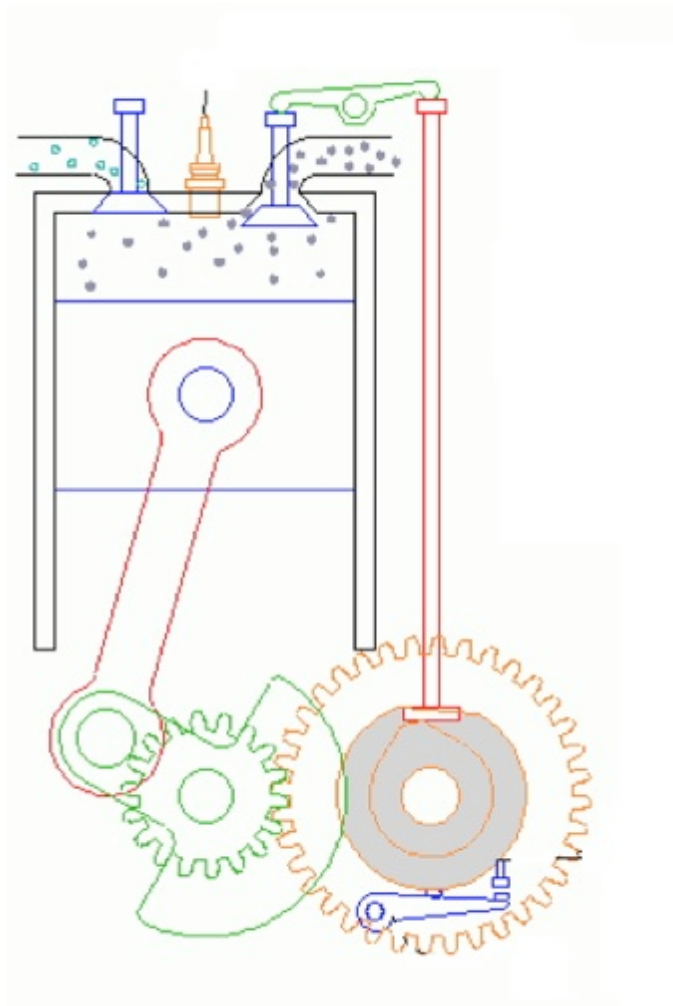
Active Field Demonstrations



Ministry of Science and Technology
Ministry of Health

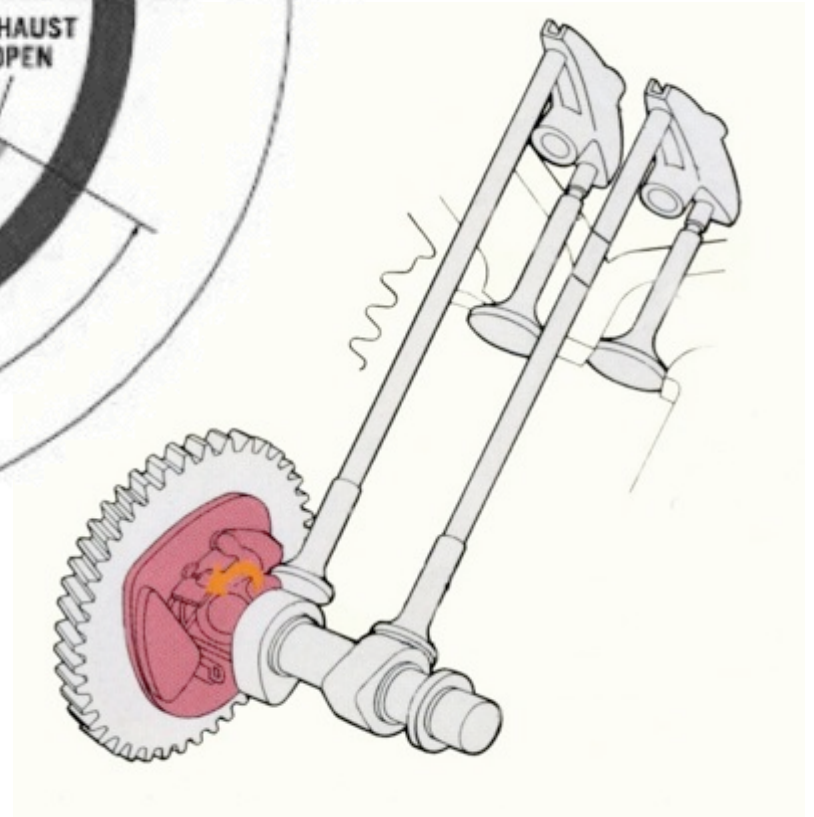
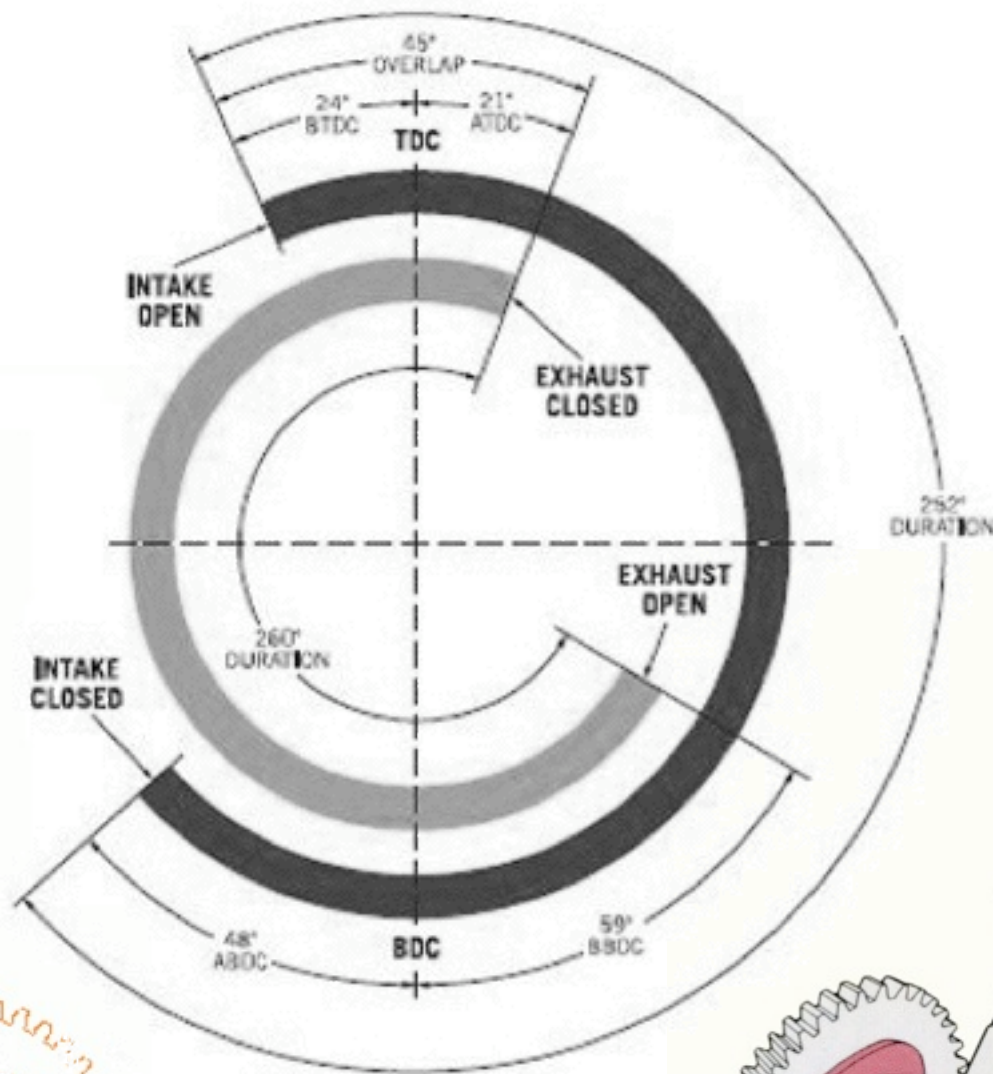
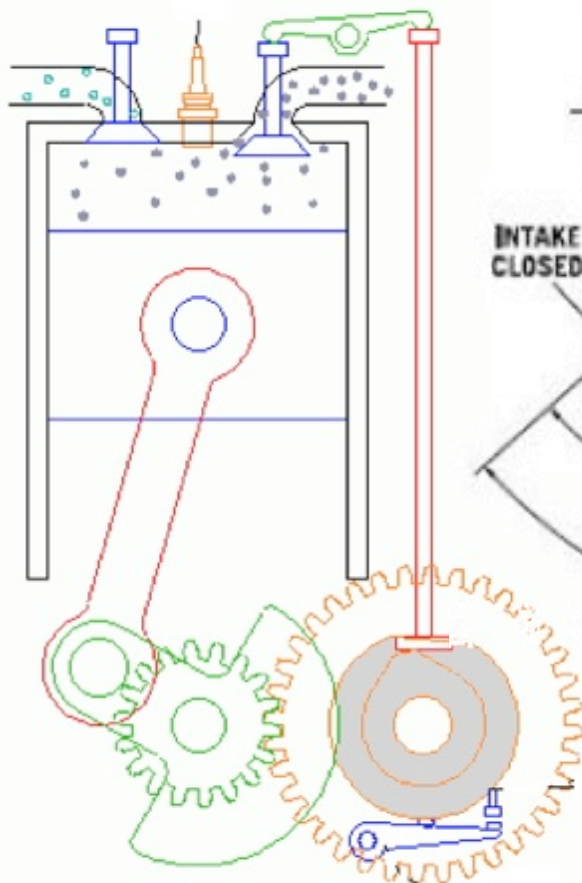


Designing and building an expander optimized for a 3kWe ORC specification: Two approaches – piston and scroll

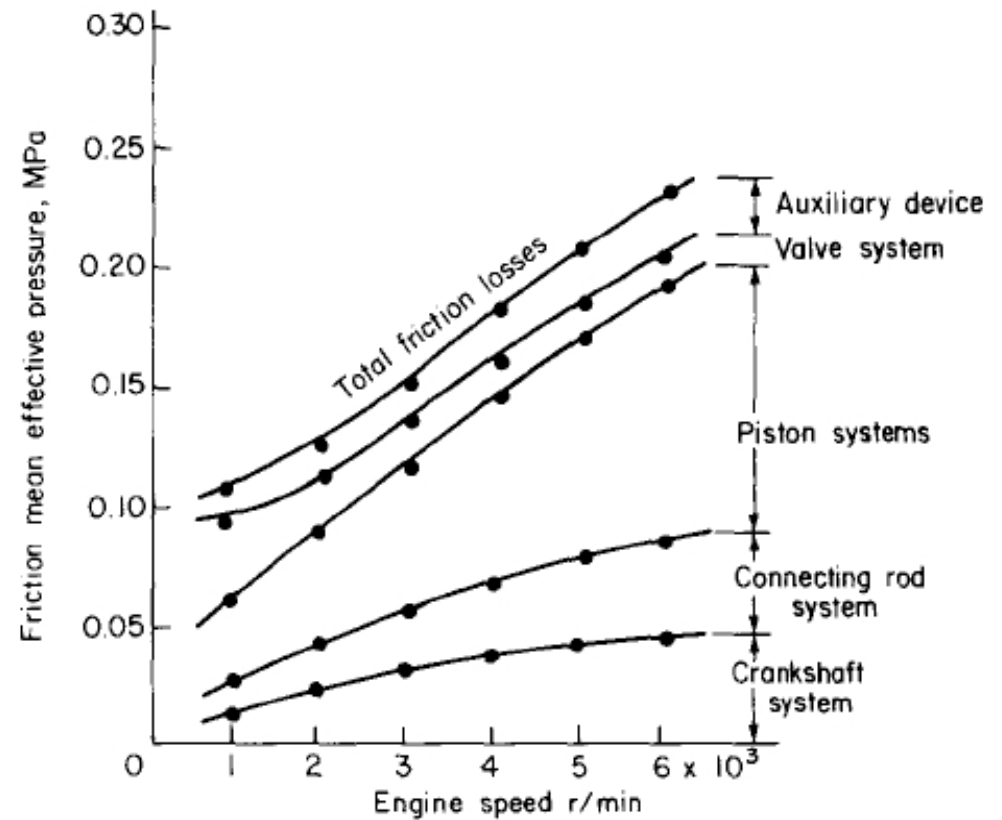
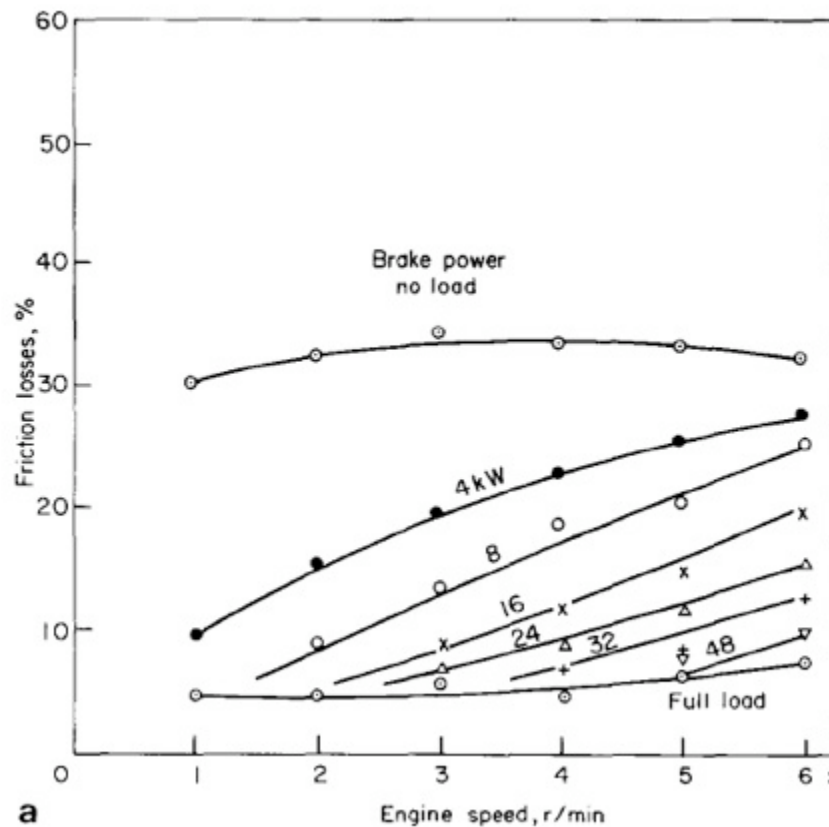


Change Timing
Gear to 1:1

Calculate new
lift curve, timing
and duration
and rework
camshaft



Friction losses in IC engines



“Back of the envelope” calculations for a typical piston machine (Honda GX120)

3600 RPM
2900 W
119 cm³ displacement
7:1 compression ratio
313 g/kWh fuel consumption
0.0075 g fuel/intake stroke
0.11 g air/intake stroke

Energy flow:

210 J supplied/stroke
48 J shaft output
2.5 J friction losses (5% fmep) / rev



Compare with conservative estimate of ORC expander:

3600 RPM
0.0037 g R245fa at 135°C / intake stroke
Delta h = 245 kJ/kg if expansion is isentropic
 $m \cdot \Delta h = 0.9 \text{ J work / rev}$
Only 60 W !

Designing a scroll from scratch

$$s_x = c1 + c2 \cdot \phi + c3 \cdot \phi^2 + c4 \cdot \phi^3 + c5 \cdot \phi^4$$

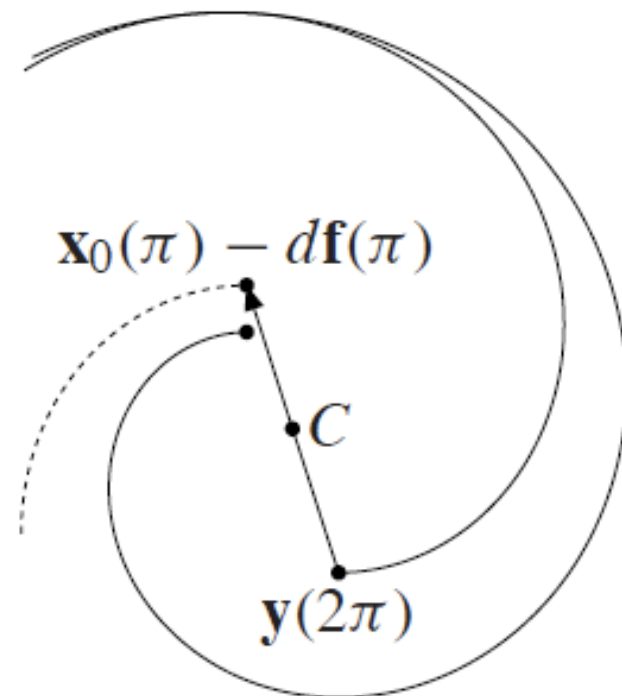
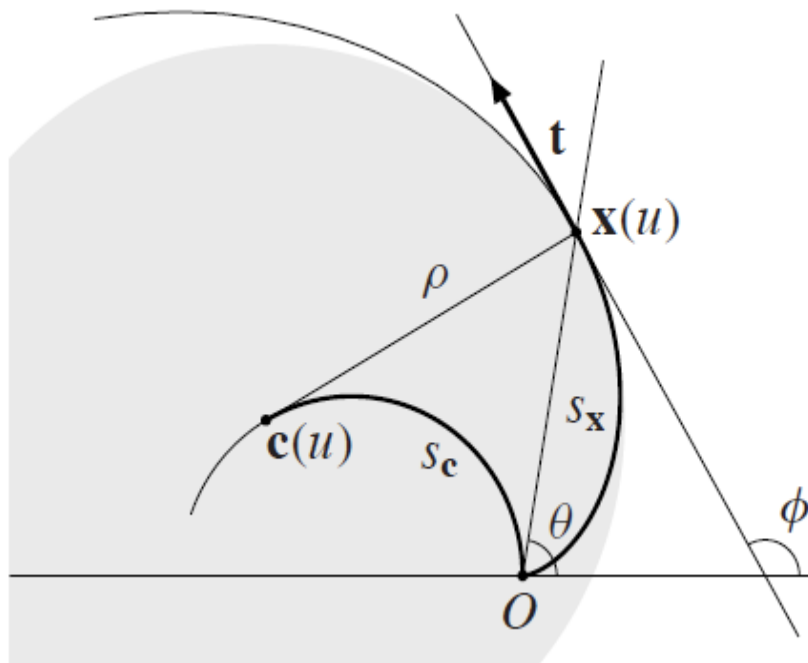
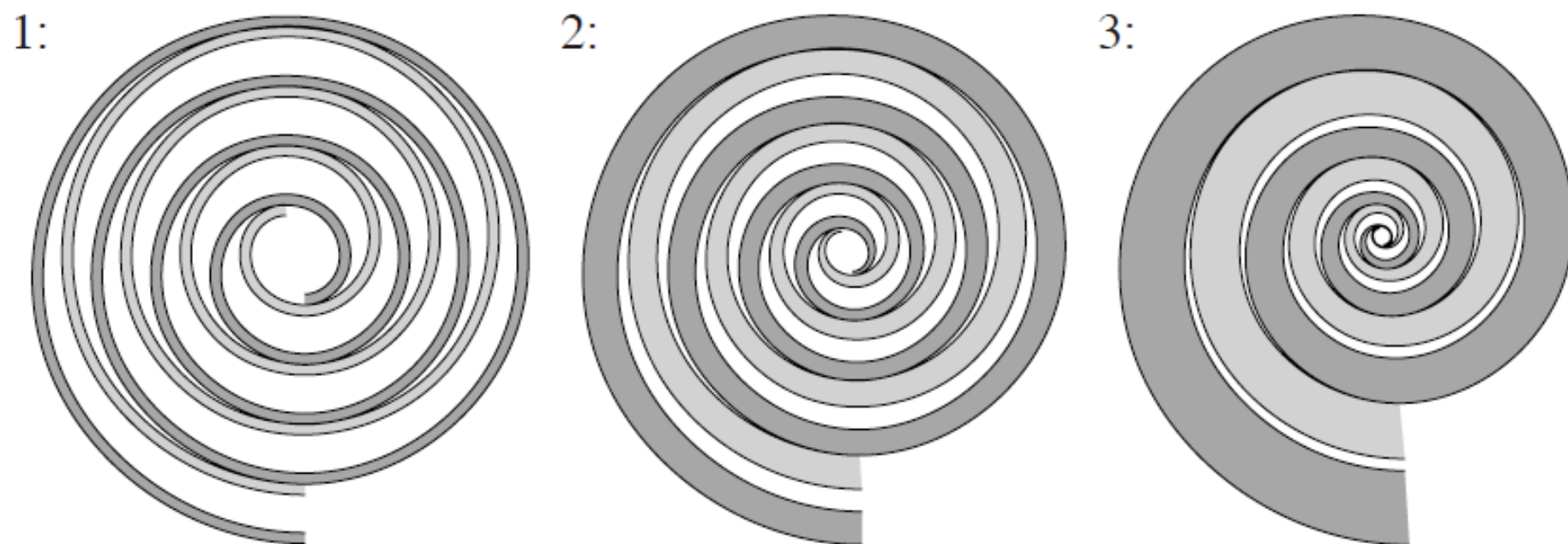


Figure 9: Reflecting a pair of mating sides in a point.



	$s(\phi)$	R	d	Δ_1	Δ_2	Δ	\bar{V}	l
1	ϕ^2	4	2.28	1.43	1.75	2.49	0.085	0.64
2	$\phi^2 + \frac{1}{30}\phi^3$	6	2	1.68	2.14	3.60	0.041	0.67
3	$\phi^2 - \frac{1}{50}\phi^3 + \frac{1}{400}\phi^4$	6	2	2.25	2.76	6.21	0.016	1.13

**What are the effects of varying coefficients of phi
(and d R and N) on figures of merit?**

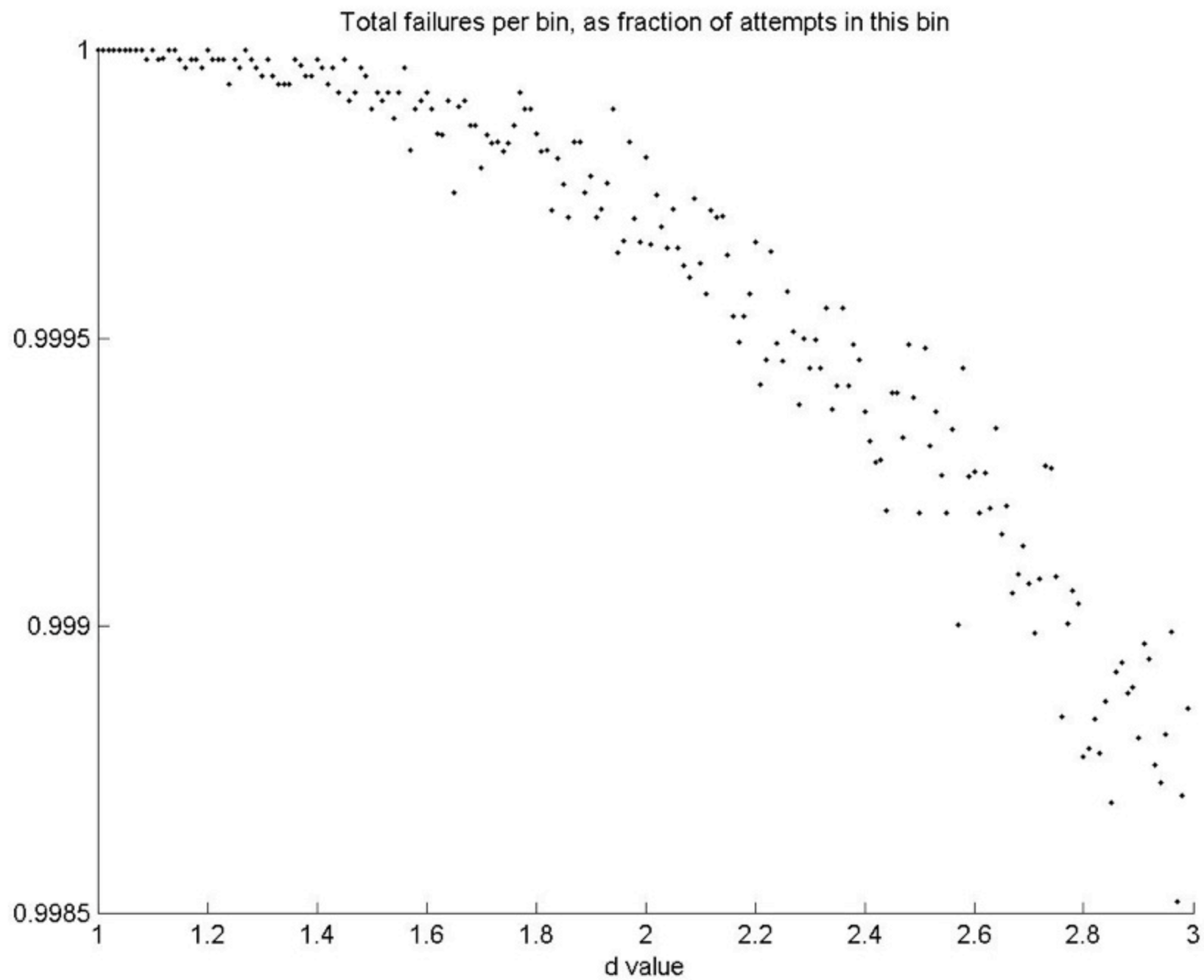
e.g. VR, leakage, scroll diameter?

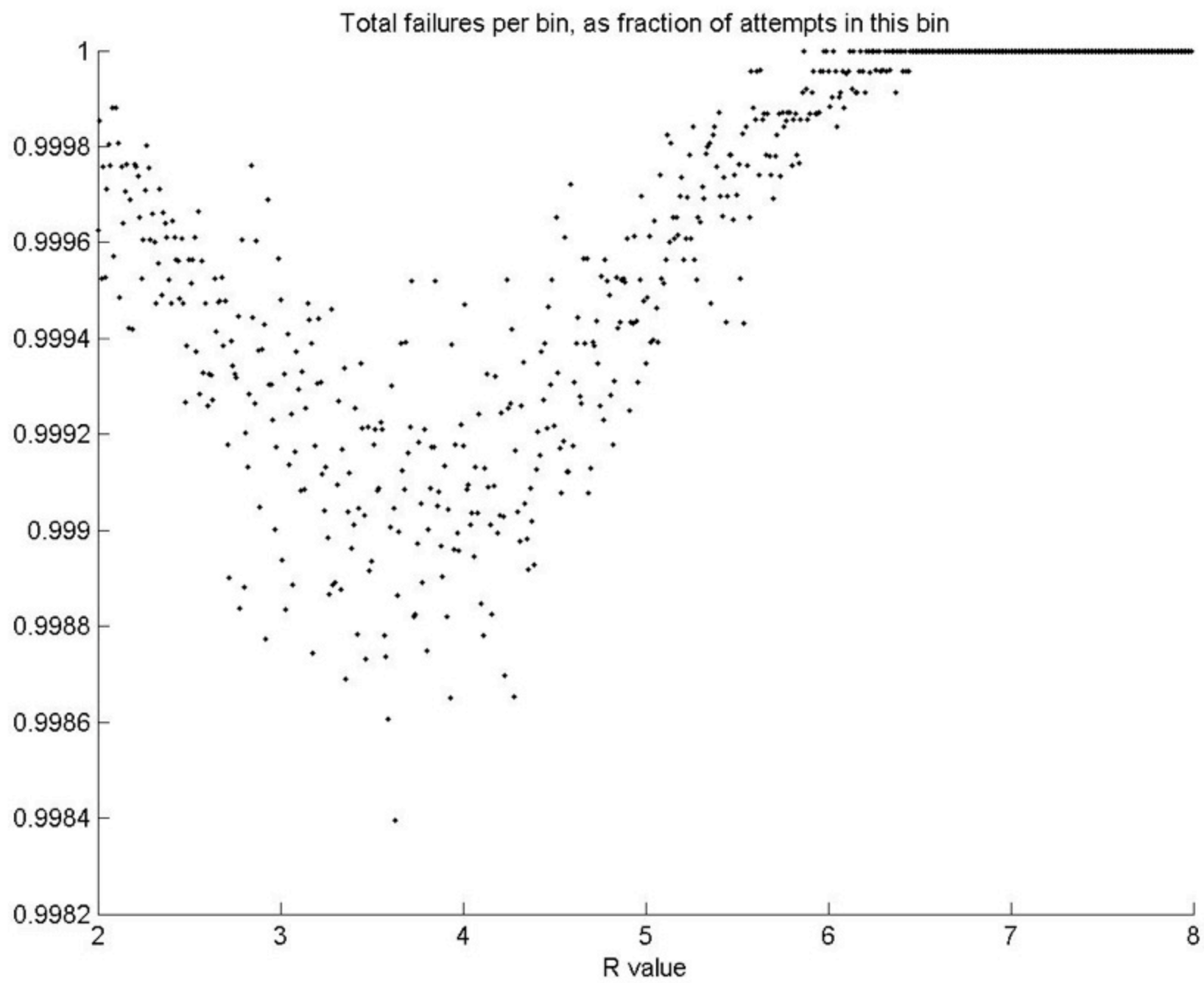
$$s_x = c1 + c2 \cdot \phi + c3 \cdot \phi^2 + c4 \cdot \phi^3 + c5 \cdot \phi^4$$

Constraints: R>2mm, DIA<300mm, wall>3mm, monotonicity

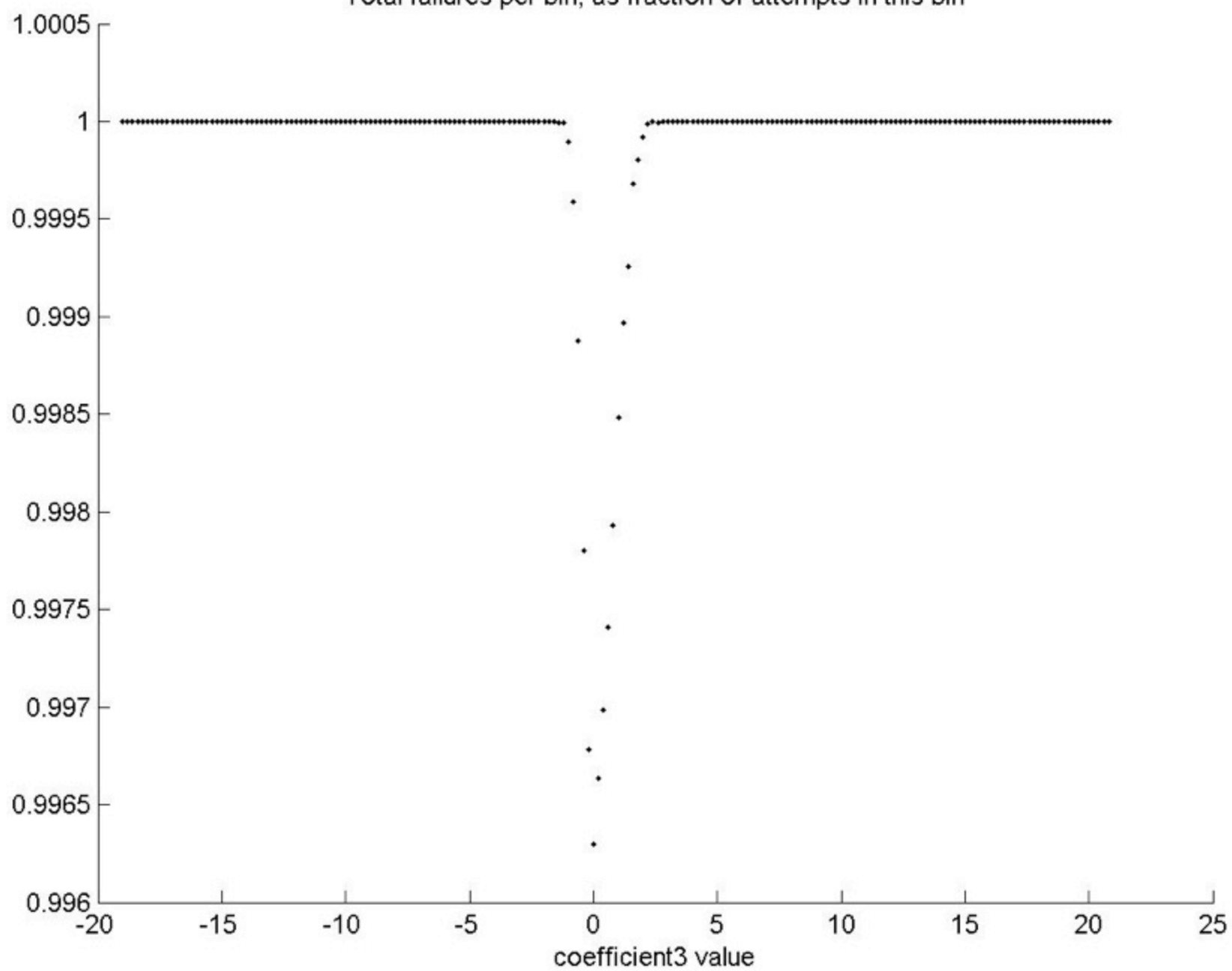
13 billion unique scrolls simulated. ~8000 viable scrolls returned.

99.9% rejected!

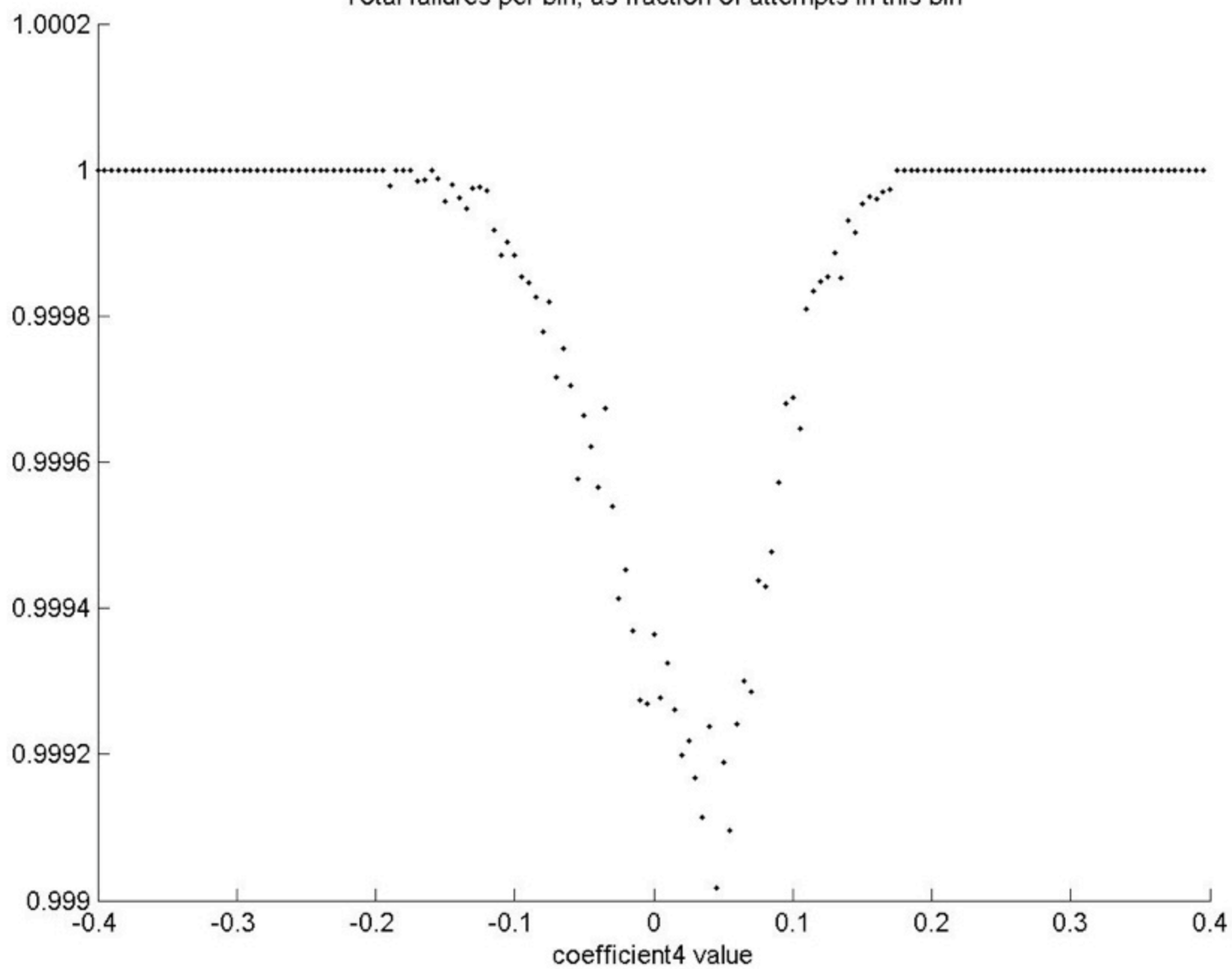




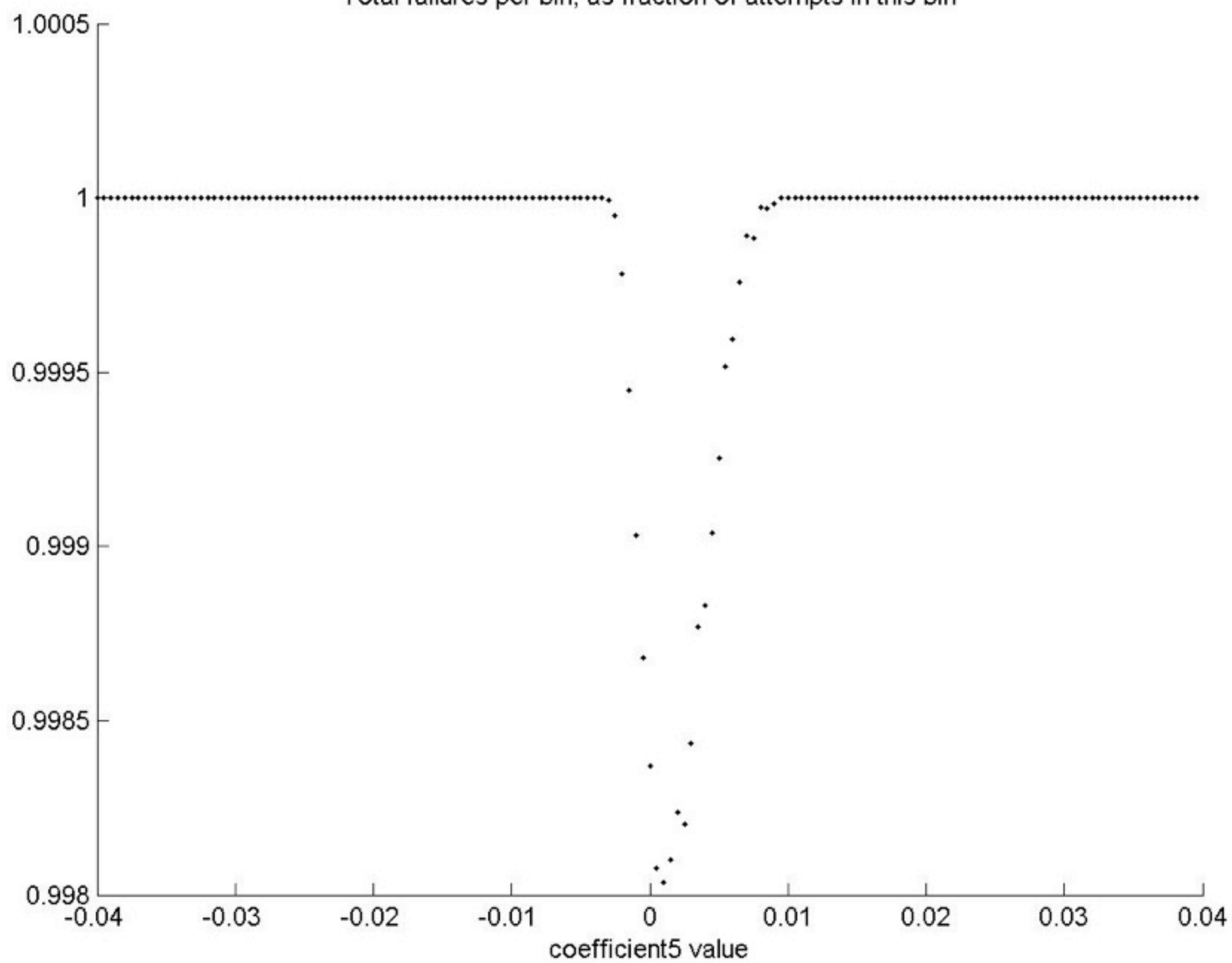
Total failures per bin, as fraction of attempts in this bin

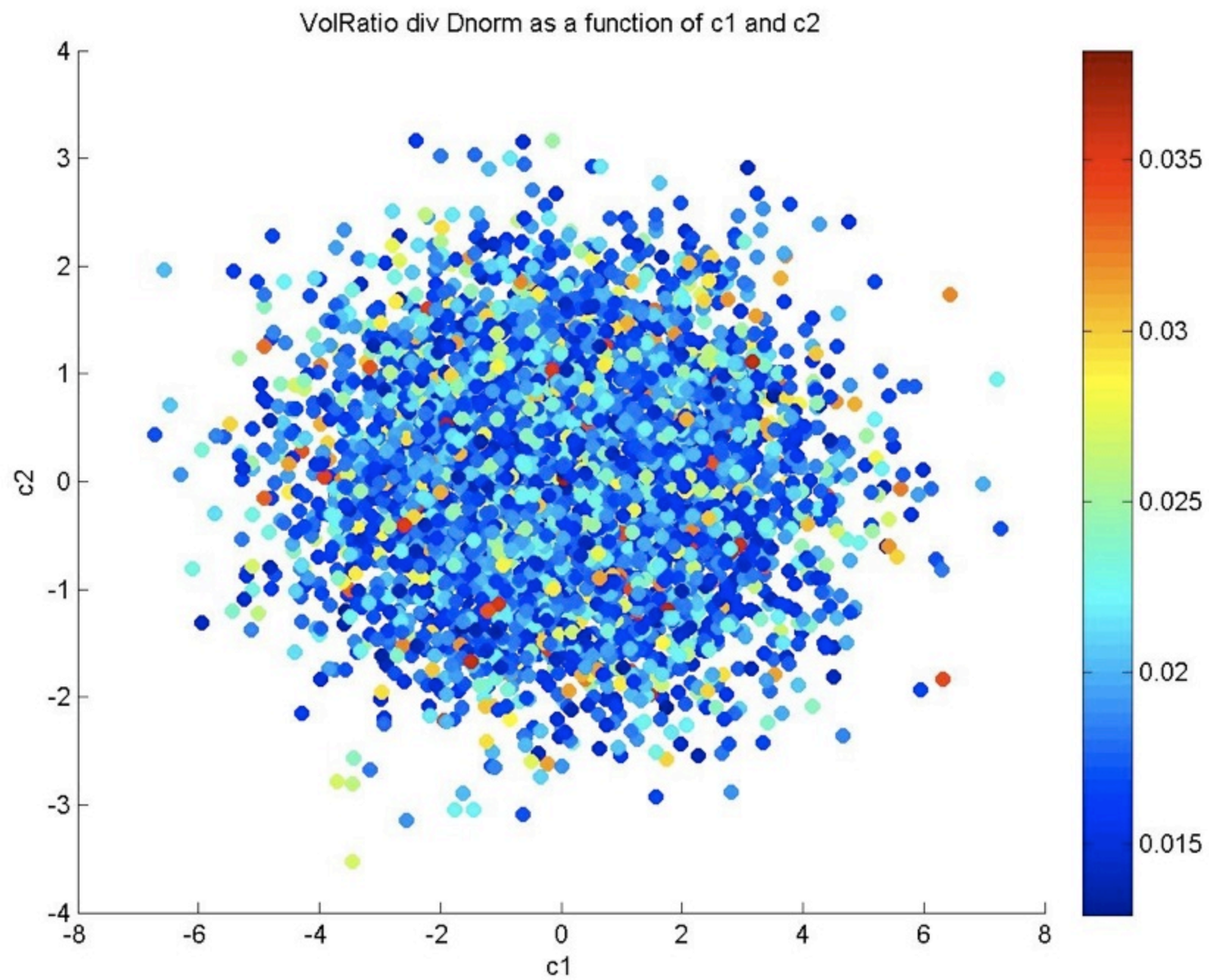


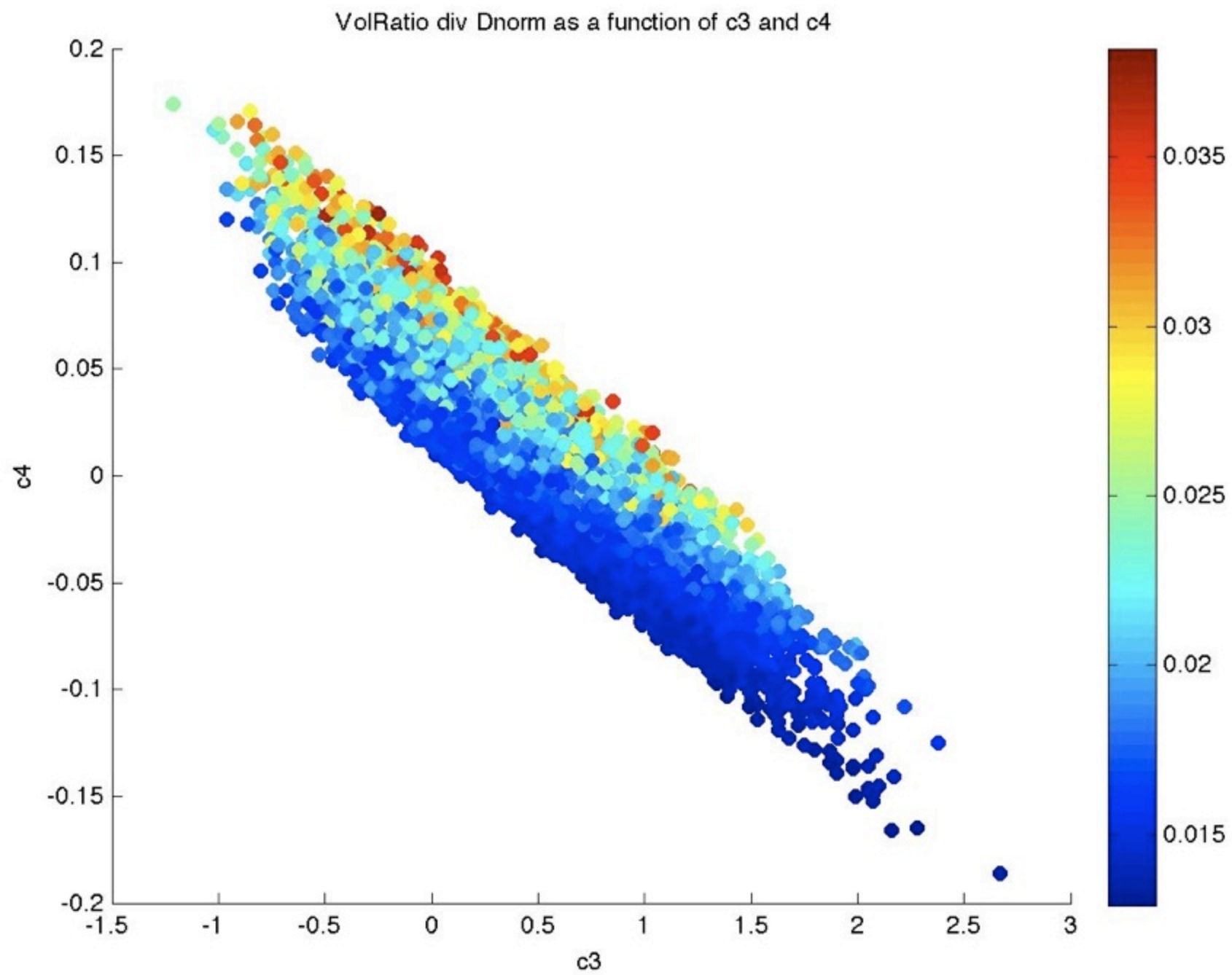
Total failures per bin, as fraction of attempts in this bin

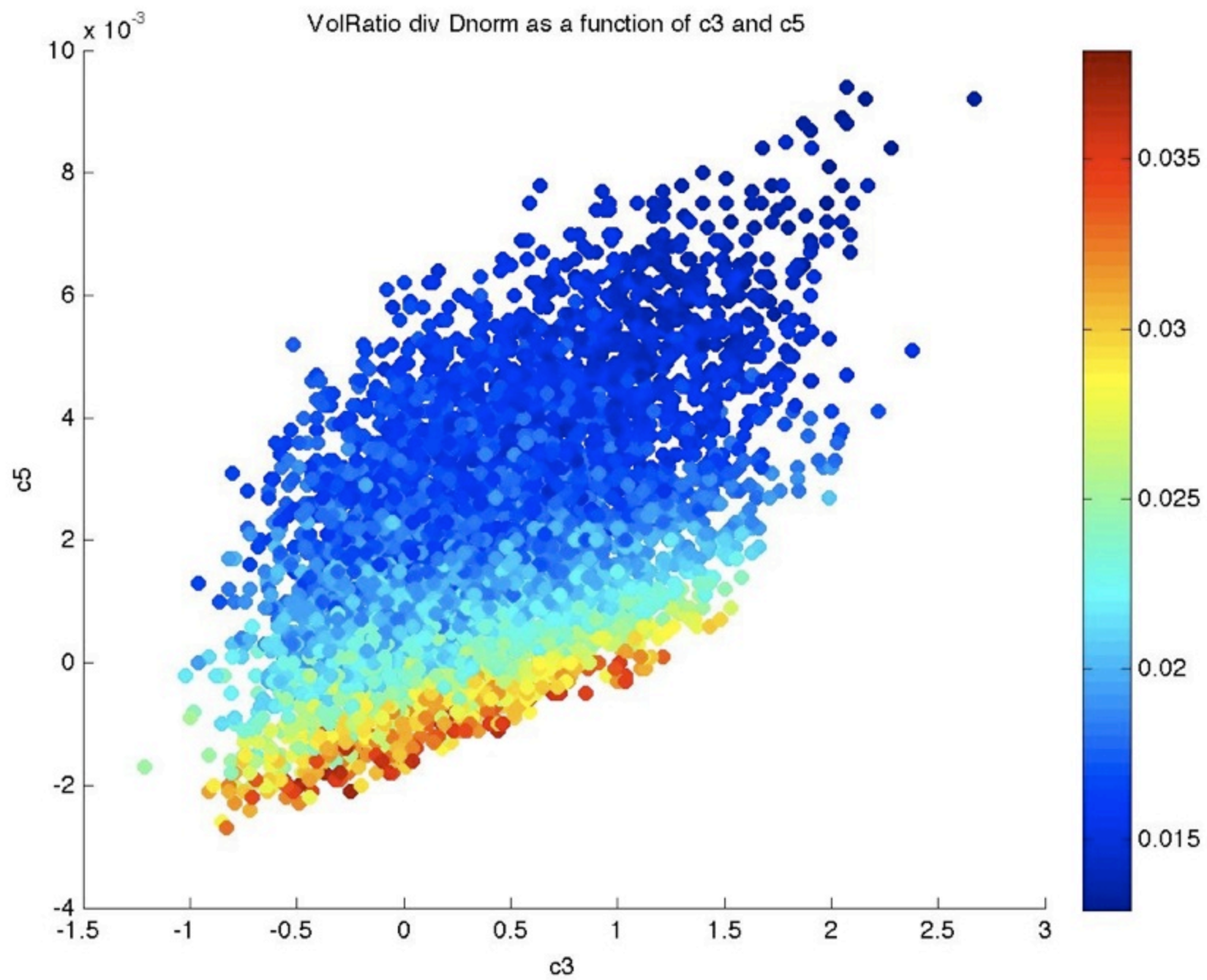


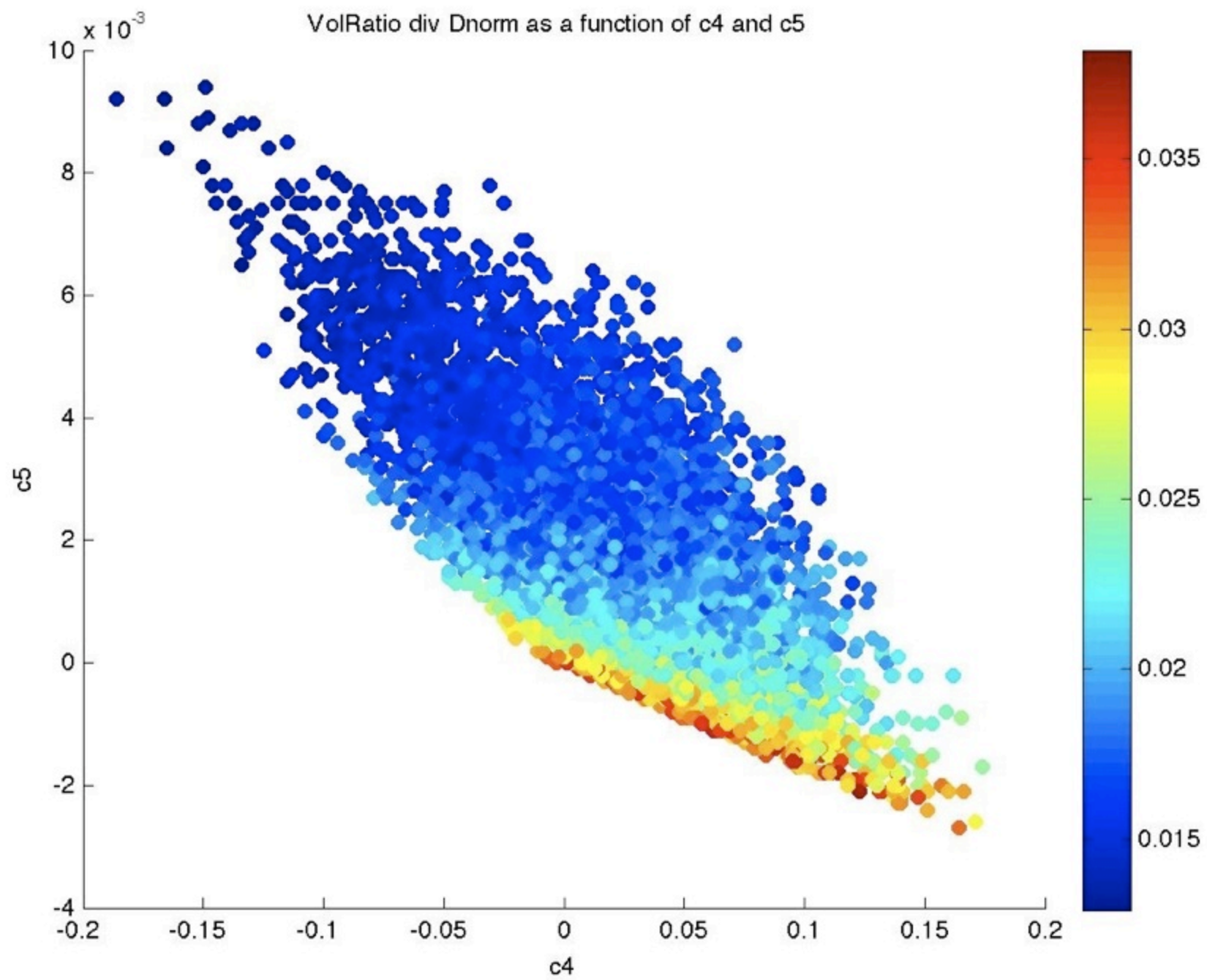
Total failures per bin, as fraction of attempts in this bin



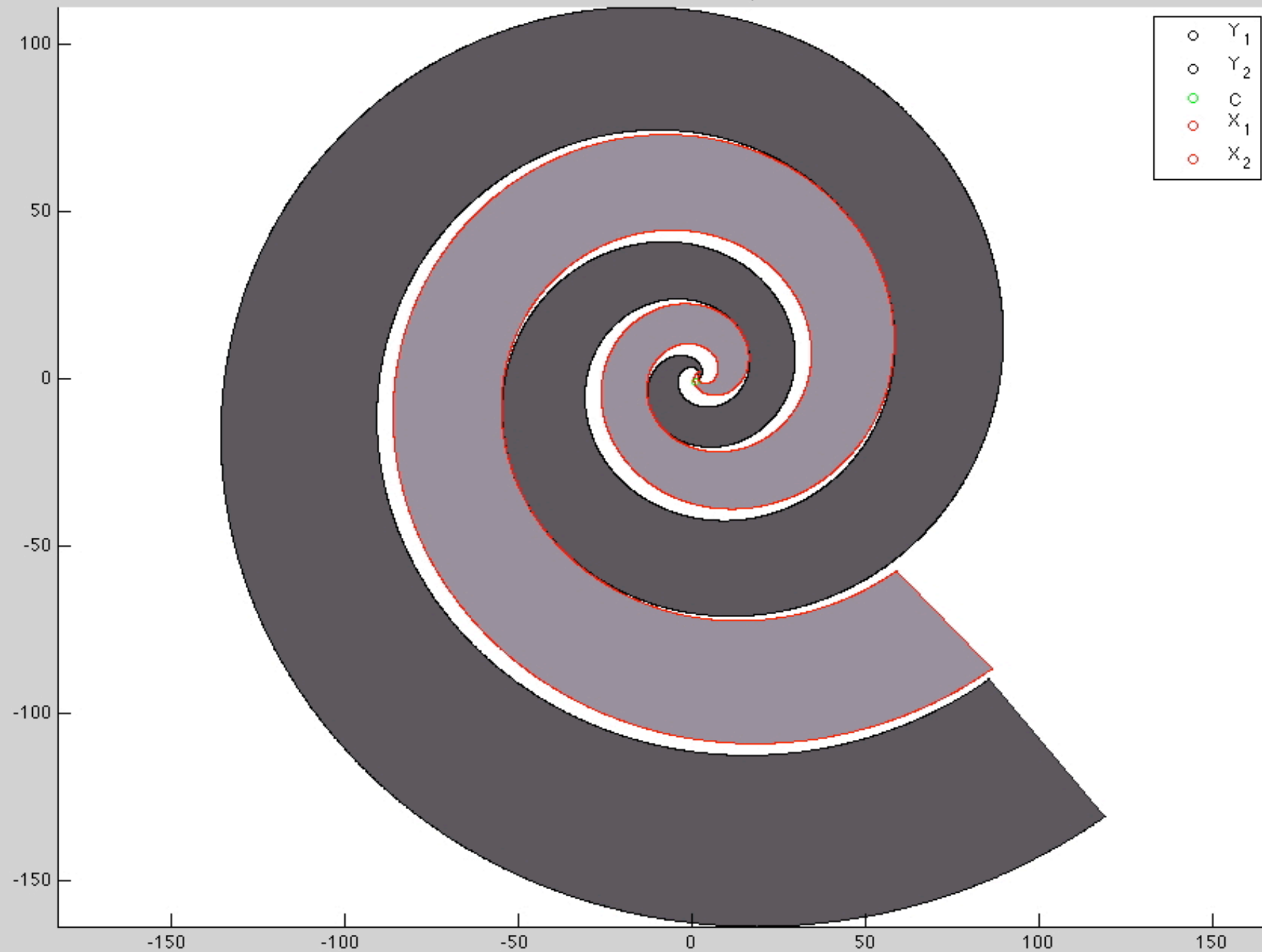




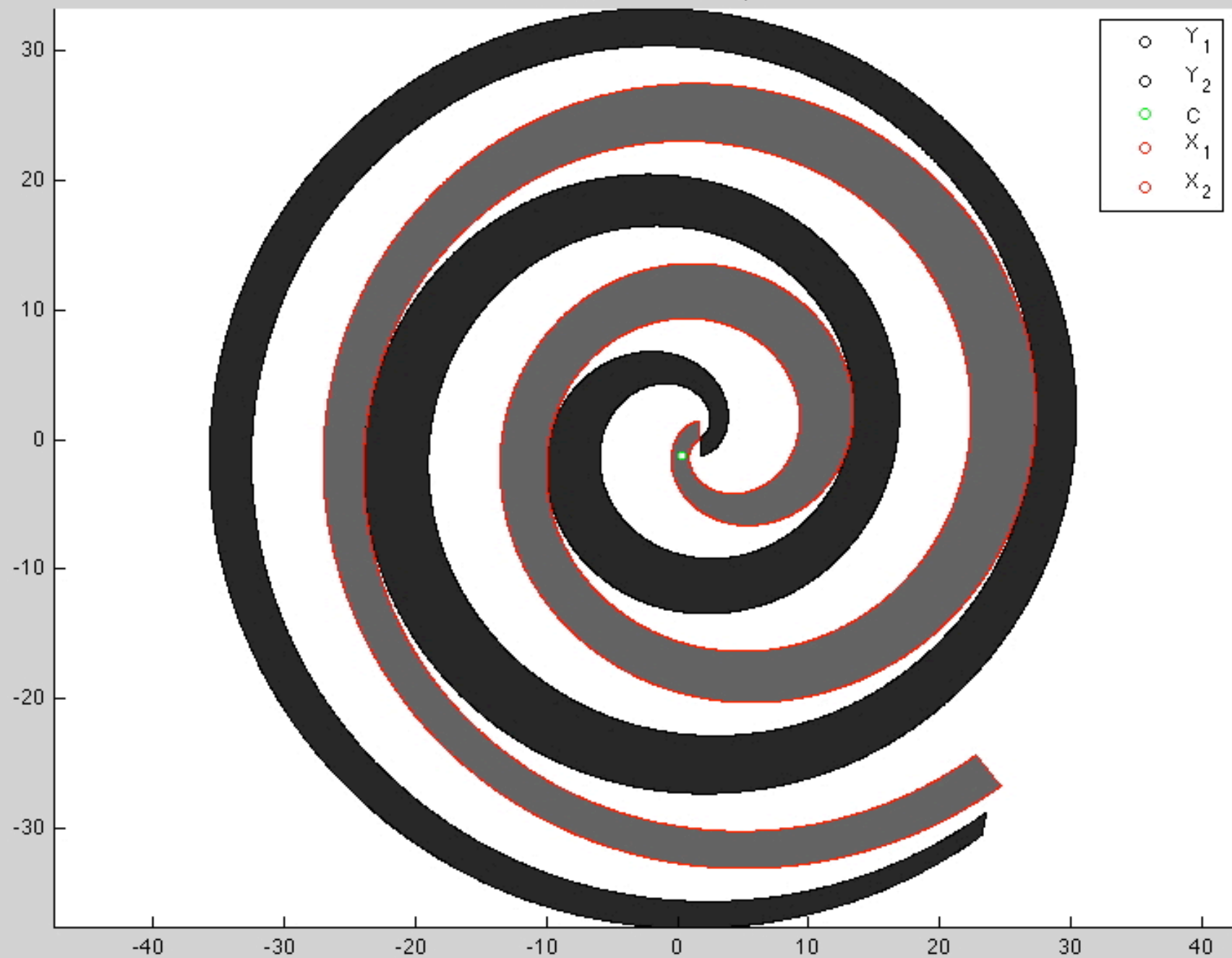




scaled scroll in its envelope

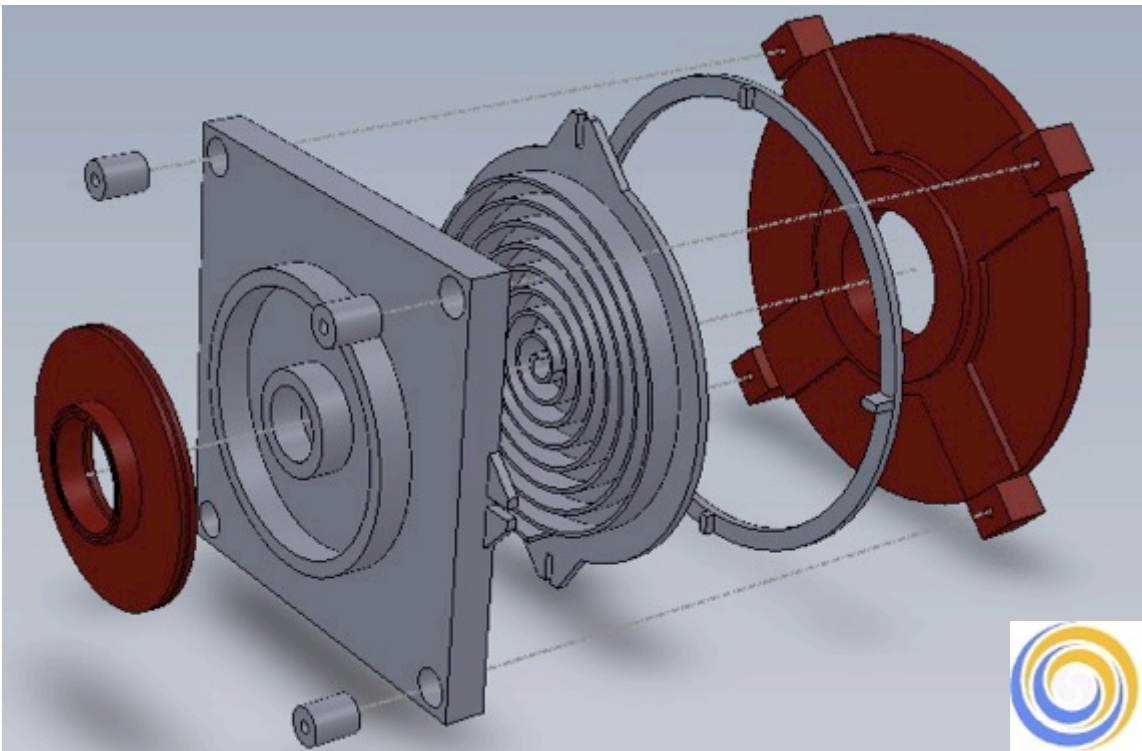


scaled scroll in its envelope



FUTURE work:

- Coupled scroll geometric model with friction and leakage model
- thermodynamic optimization of a scroll design for a particular ORC operating specification (3kWe Solar input $\sim 150^{\circ}\text{C}$)
- Construct prototype and test it in solar ORC pilot system



Thank You!