Argonne
NATIONAL
LABORATORY

... for a brighter future

Optimizing Economy of Scale for the STAR Energy Supply Architecture

IAEA 2nd CRP Meeting
on
Small Reactors without Onsite Refueling
June 4-8, 2007

David C. Wade
Argonne National Laboratory

U.S. Department
of Energy

UChicago ▸
Argonne LLC

A Market for Small Reactors

- Three Recent IAEA – Sponsored Conferences Concerning Nuclear Deployments in Developing Countries
  - Mumbai (1998)
  - Paris (2005)
  - Vienna (2006)
- 65 Developing Countries Participated in one or more conferences
  - (see tables attached)
- Generally Speaking these countries are characterized by:
  - Lower (or vastly lower) energy use/capita-year than Developed Countries
  - Low GDP/capita-year
  - Faster growth rate of GDP than in developed countries
- Entire Country Grid is ≤ 4 GW_e in
  - Half of N. Africa + Middle east countries attending the conferences
  - All but 1 of Sub-Sahara Africa countries
  - About a third of east European countries
  - About half of Central and S. American countries
- Rule of Thumb: Any single power plant ≤ 10 to 15% of Grid
- Conclusion: Vast Potential Market for Reactor Sized at ≤ 200 MW_e

Developing Countries Interested in Nuclear Deployments as Evidenced by Attendance at Three Recent IAEA Meetings

Country	IAEA Meeting Participation			Statistics						
	Mumbai	**Paris**	**Vienna**	**Pop 10^6**	**GDP $10^9\$$**	**%/y**	$\frac{\text{toe}}{\text{cap y}}$	**Energy Export**	$\frac{\text{TW}_e\text{ hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
East Asia and Pacific										
China	✓	M	✓	1296	1715	10.5	1.24	–	2055	1585
Philippines	✓	✓		81.6	88.6	5.4	0.54	–	48.7	597
Republic of Korea	✓	M	✓	22.4	10.5	4.8	4.43	–	355	7391

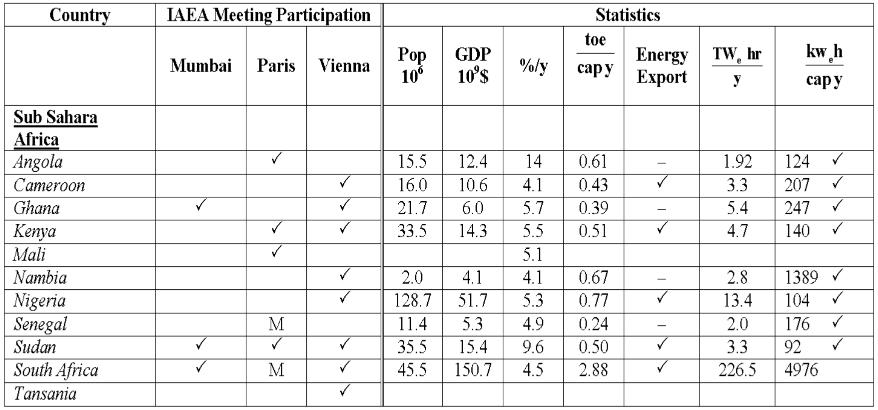
Country	IAEA Meeting Participation			Statistics						
	Mumbai	**Paris**	**Vienna**	**Pop 10^6**	**GDP $10^9\$$**	**%/y**	$\frac{\text{toe}}{\text{cap y}}$	**Energy Export**	$\frac{\text{TW}_e\text{ hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
South Asia										
Bangladesh	✓	M	–	139	56	6.1	0.16	–	19.4	140
India	✓	M	✓	1,080	581	8.5	0.53	–	494	457
Indonesia	✓	M	✓	218	197	5.4	0.80	✓	104	478
Malaysia	✓	✓	✓	25	107	5.5	2.3	✓	79	3166
Pakistan		M	–	152	86	6.5	0.49		65	425
Viet Nam		M	✓	82	41	7.8	0.61	✓	41	501

Country	IAEA Meeting Participation			Statistics						
	Mumbai	**Paris**	**Vienna**	**Pop 10^6**	**GDP $10^9\$$**	**%/y**	$\frac{\text{toe}}{\text{cap y}}$	**Energy Export**	$\frac{\text{TW}_e\text{ hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
Central Asia										
Afghanistan		✓				8.4				
Kazakhstan	✓			15	27	8.5	3.7	✓	54	3626
Tajikistan		✓		6.4	1.4	7.0	0.52	✓	14.4	2240 ✓

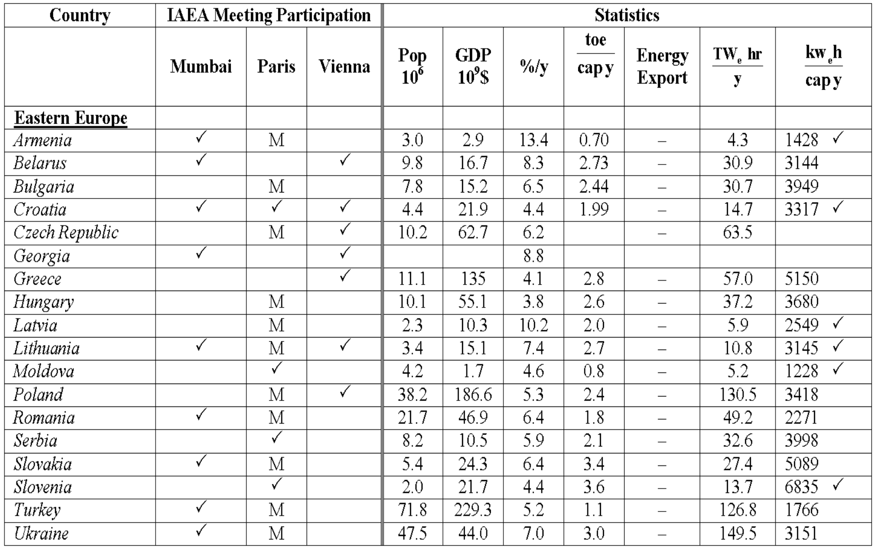
Country	IAEA Meeting Participation			Statistics						
	Mumbai	**Paris**	**Vienna**	**Pop 10^6**	**GDP $10^9\$$**	**%/y**	$\frac{\text{toe}}{\text{cap y}}$	**Energy Export**	$\frac{\text{TW}_e\text{ hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
N. Africa + Middle East										
Algeria		✓	✓	32	64	5.6	1.0	✓	26.3	812 ✓
Egypt	✓	M	✓	73	117	5.7	0.78	✓	88.2	1215
Iran	✓	M	✓	67	126	5.0	2.18	✓	137	2045
Iraq	–	✓	–							
Israel	✓			6.8	121	4.5	3.05	–	46	6808
Jordan		M	✓	5.4	10.6	6.0	1.2	–	8.6	1575 ✓
Kuwait	✓			2.5	43.5	8.0	10.2	✓	36.8	14,952
Libya		✓	–			8.1				
Morocco		M	✓	29.8	40.2	6.7	0.38	–	17.7	595 ✓
Saudi Arabia		M	–	24.0	214.9	5.9	5.9	✓	148	6181
Syria	✓	✓	✓	18.6	20.7	2.9	0.99	✓	24.5	1317 ✓
Tunisia	✓	–	✓	9.9	23.2	4.0	0.88	–	11.5	1157 ✓
U. Arab Emirates		✓	✓	4.3	95.8	10.2	10.14	✓	49.0	11,331
Yemen		✓	✓	20.3	10.9	3.2	0.31	✓	3.36	165 ✓

✓ in last column means that $\frac{\text{TW}_e\text{ hr}}{\text{y}} < 25$ which means that Grid is <4 GW$_e$ (assumes CF = 0.7)

Developing Countries Interested in Nuclear Deployments as Evidenced by Attendance at Three Recent IAEA Meetings (Cont'd.)

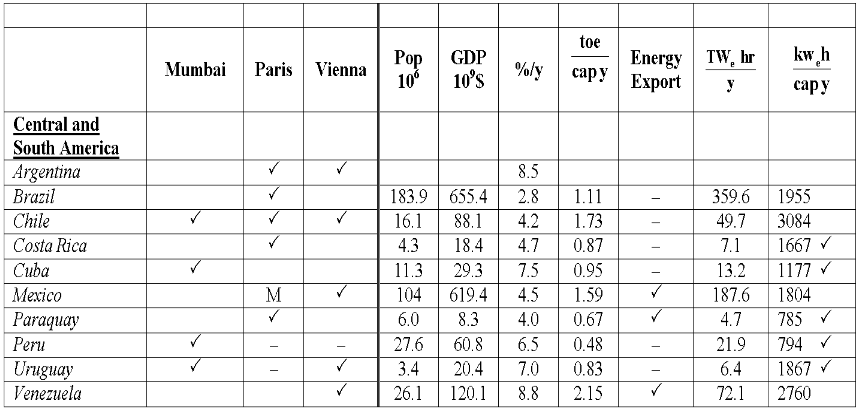


Country	IAEA Meeting Participation			Statistics						
	Mumbai	Paris	Vienna	Pop 10^6	GDP $10^9\$$	%/y	$\frac{\text{toe}}{\text{cap y}}$	Energy Export	$\frac{\text{TW}_e\text{ hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
Sub Sahara Africa										
Angola		✓		15.5	12.4	14	0.61	–	1.92	124 ✓
Cameroon			✓	16.0	10.6	4.1	0.43	✓	3.3	207 ✓
Ghana	✓		✓	21.7	6.0	5.7	0.39	–	5.4	247 ✓
Kenya		✓	✓	33.5	14.3	5.5	0.51	✓	4.7	140 ✓
Mali		✓				5.1				
Nambia			✓	2.0	4.1	4.1	0.67	–	2.8	1389 ✓
Nigeria			✓	128.7	51.7	5.3	0.77	✓	13.4	104 ✓
Senegal		M		11.4	5.3	4.9	0.24	–	2.0	176 ✓
Sudan	✓	✓	✓	35.5	15.4	9.6	0.50	✓	3.3	92 ✓
South Africa	✓	M	✓	45.5	150.7	4.5	2.88	✓	226.5	4976
Tansania			✓							

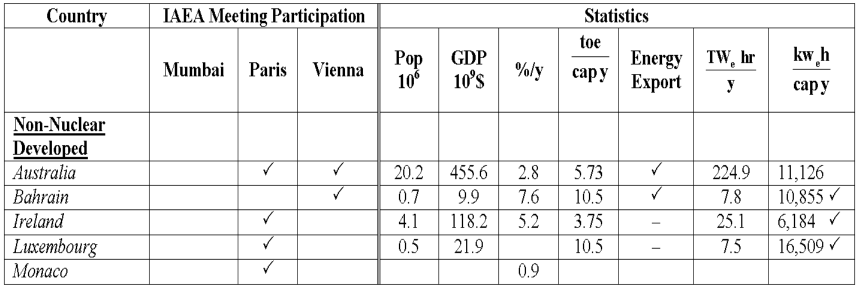


Country	IAEA Meeting Participation			Statistics						
	Mumbai	Paris	Vienna	Pop 10^6	GDP $10^9\$$	%/y	$\frac{\text{toe}}{\text{cap y}}$	Energy Export	$\frac{\text{TW}_e\text{ hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
Eastern Europe										
Armenia	✓	M		3.0	2.9	13.4	0.70	–	4.3	1428 ✓
Belarus	✓		✓	9.8	16.7	8.3	2.73	–	30.9	3144
Bulgaria		M		7.8	15.2	6.5	2.44	–	30.7	3949
Croatia	✓	✓	✓	4.4	21.9	4.4	1.99	–	14.7	3317 ✓
Czech Republic		M	✓	10.2	62.7	6.2		–	63.5	
Georgia	✓		✓			8.8				
Greece			✓	11.1	135	4.1	2.8	–	57.0	5150
Hungary		M		10.1	55.1	3.8	2.6	–	37.2	3680
Latvia		M		2.3	10.3	10.2	2.0	–	5.9	2549 ✓
Lithuania	✓	M	✓	3.4	15.1	7.4	2.7	–	10.8	3145 ✓
Moldova		✓		4.2	1.7	4.6	0.8	–	5.2	1228 ✓
Poland		M	✓	38.2	186.6	5.3	2.4	–	130.5	3418
Romania	✓	M		21.7	46.9	6.4	1.8	–	49.2	2271
Serbia		✓		8.2	10.5	5.9	2.1	–	32.6	3998
Slovakia	✓	M		5.4	24.3	6.4	3.4	–	27.4	5089
Slovenia		✓		2.0	21.7	4.4	3.6	–	13.7	6835 ✓
Turkey	✓	M		71.8	229.3	5.2	1.1	–	126.8	1766
Ukraine	✓	M		47.5	44.0	7.0	3.0	–	149.5	3151

Developing Countries Interested in Nuclear Deployments as Evidenced by Attendance at Three Recent IAEA Meetings (Cont'd.)

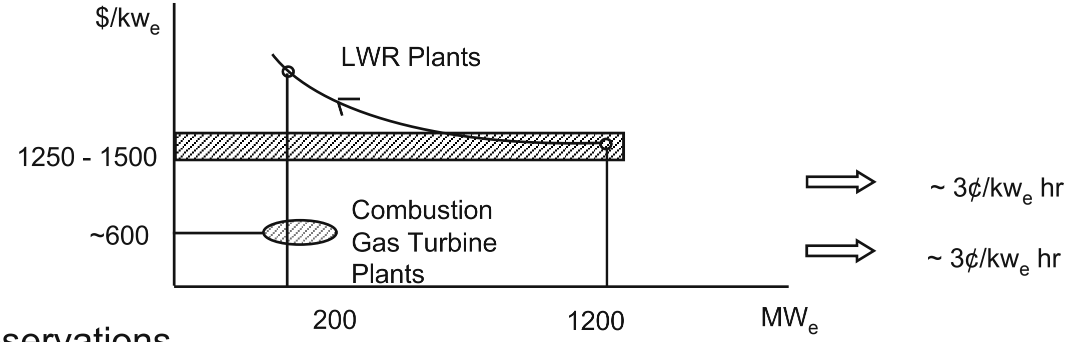


	Mumbai	**Paris**	**Vienna**	**Pop 10^6**	**GDP 10^9\$**	**%/y**	$\frac{\text{toe}}{\text{cap y}}$	**Energy Export**	$\frac{TW_e\ \text{hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
Central and South America										
Argentina		✓	✓			8.5				
Brazil		✓		183.9	655.4	2.8	1.11	–	359.6	1955
Chile	✓	✓	✓	16.1	88.1	4.2	1.73	–	49.7	3084
Costa Rica		✓		4.3	18.4	4.7	0.87	–	7.1	1667 ✓
Cuba	✓			11.3	29.3	7.5	0.95	–	13.2	1177 ✓
Mexico		M	✓	104	619.4	4.5	1.59	✓	187.6	1804
Paraquay		✓		6.0	8.3	4.0	0.67	✓	4.7	785 ✓
Peru	✓	–	–	27.6	60.8	6.5	0.48	–	21.9	794 ✓
Uruguay	✓	–	✓	3.4	20.4	7.0	0.83	–	6.4	1867 ✓
Venezuela			✓	26.1	120.1	8.8	2.15	✓	72.1	2760

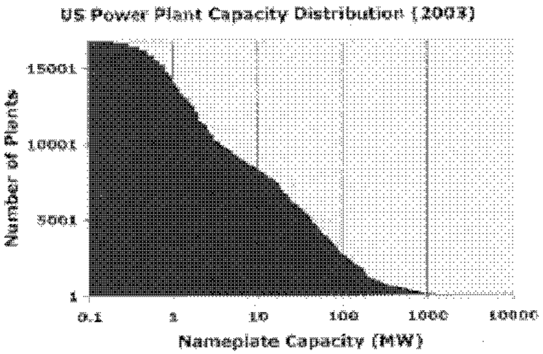


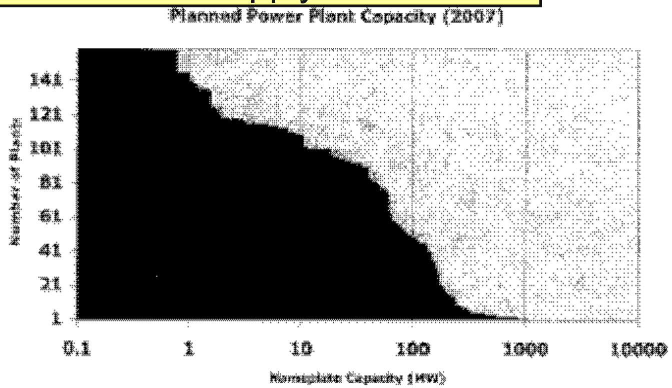
Country	**IAEA Meeting Participation**			**Statistics**						
	Mumbai	**Paris**	**Vienna**	**Pop 10^6**	**GDP 10^9\$**	**%/y**	$\frac{\text{toe}}{\text{cap y}}$	**Energy Export**	$\frac{TW_e\ \text{hr}}{\text{y}}$	$\frac{\text{kw}_e\text{h}}{\text{cap y}}$
Non-Nuclear Developed										
Australia		✓	✓	20.2	455.6	2.8	5.73	✓	224.9	11,126
Bahrain			✓	0.7	9.9	7.6	10.5	✓	7.8	10,855 ✓
Ireland		✓		4.1	118.2	5.2	3.75	–	25.1	6,184 ✓
Luxembourg		✓		0.5	21.9		10.5	–	7.5	16,509 ✓
Monaco		✓				0.9				

200 MW$_e$: Loss of Economy of Scale ≡ Loss of Competitiveness Is it True?!



- Observations
  - Capital cost depends on technology choices
  - Cost of energy depends on entire fuel/converter supply chain





Ning Li (LANL) personal communication

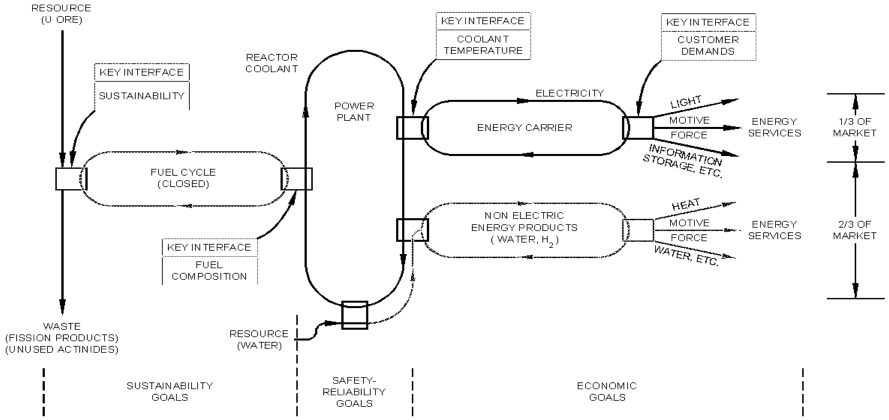
- Observations
  - LWR's are outliers on plant size: Even in Developed Countries
  - A market for small power plants exists: Even in Developed Countries

So:

No, -- it is not necessarily true; but you have to optimize the supply chain as a whole

Approach for Optimizing The Economy of Scale (EOS) Curve for an Energy Supply Architecture

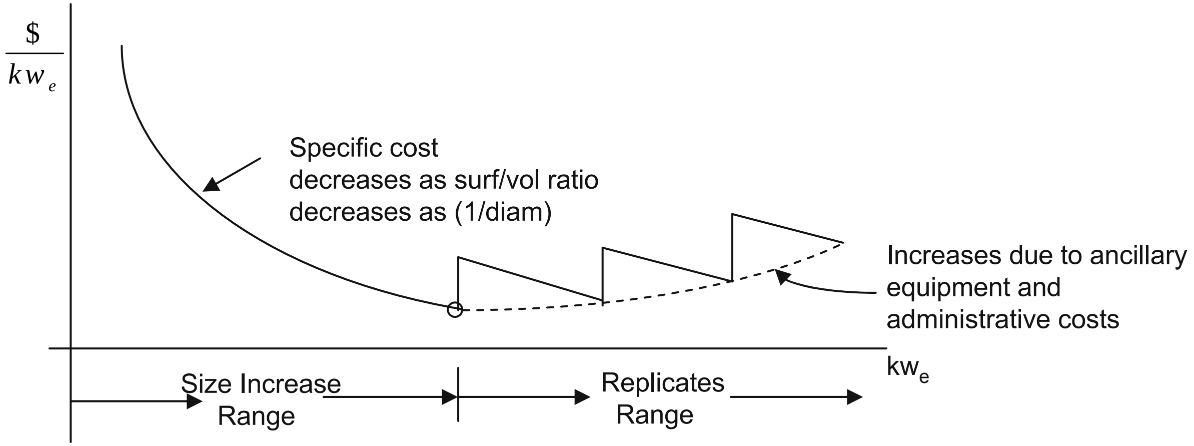
Nature of Energy Supply Chains



GENERATION 4 GOALS FOR NUCLEAR ENERGY SUPPLY

- The Energy Supply chain
  - Starts at the resource base
  - Ends at the energy user
  - Energy Carriers links
  - Energy Converter nodes

Each Link Has Its Own Economy of Scale Curve



Optimizing The Energy Supply Chain as a Whole

- 1st – Start at the end user to determine required size

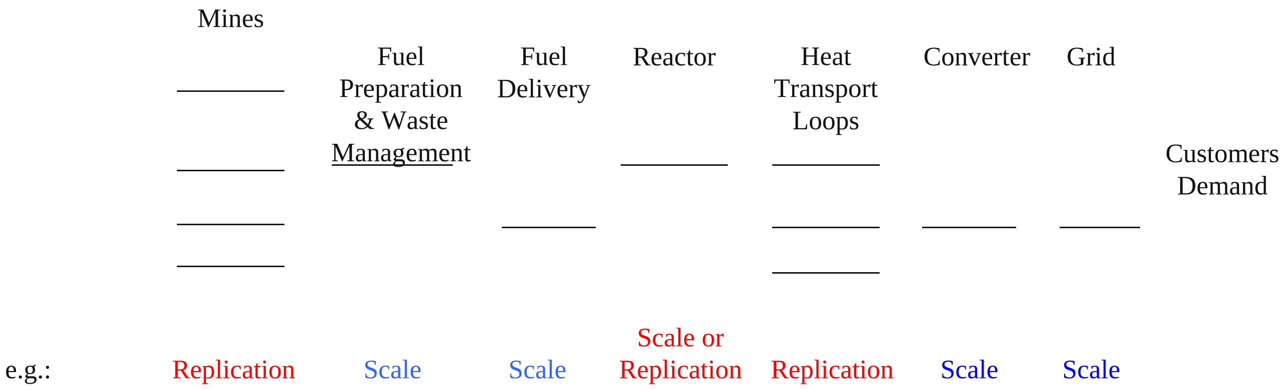
  Marchetti has observed that the scale of an energy supply chain will grow until the marginal revenue attained by further expansion is exceeded by the marginal cost of further expansion. For a local power plant this demand is the product of

  $$\left(\frac{electricity\ use}{capita}\right)*\left(population\ density\right)*\left(maximum\ area\ covered\ by\ the\ local\ grid\right)$$

  $$i.e., by\ the\ product:$$

  $$\frac{MW_e hr}{capita\ year}*\frac{capita}{acre}*acres\ served\ by\ the\ grid$$

- 2nd – Work backwards in the chain link by link, determining each link's min point in its EOS curve
- 3rd – Connect carriers and hubs – each as close to min of it's EOS curve as possible (via size or via replication)



	Mines	Fuel Preparation & Waste Management	Fuel Delivery	Reactor	Heat Transport Loops	Converter	Grid	Customers Demand
e.g.:	Replication	Scale	Scale	Scale or Replication	Replication	Scale	Scale	

Three Approaches Are Available to Lower a Link's EOS Curve

For The Energy Transport and Delivery Chain Per Se:

- Energy Converter Links

$$\frac{\$}{kw_e} \equiv \frac{\$/m^3}{kw_t/m^3} * \frac{1}{kw_e/kw_t} \sim \boxed{\frac{(decrease\ surface/volume)}{\begin{pmatrix} increase \\ power\ density \end{pmatrix} * \begin{pmatrix} increase \\ conversion\ efficiency \end{pmatrix}}}$$

- Energy Carrier Links

$$\frac{\$}{kw_e} \equiv \frac{\$}{\dfrac{m^3\,piping\ commodity}{m^2\ flow\ area}} * \frac{1}{\rho * area * vel\ \dfrac{kg\ carrier}{\sec m^2\ flow\ area}} * \frac{1}{\dfrac{kw_e\,\sec}{kg\ carrier}}$$

$$\boxed{\sim \frac{1}{\dfrac{cost\ of\ piping}{unit\ flow\ area}} * \frac{1}{\begin{matrix} higher\ energy \\ density\ carrier \end{matrix}} * \frac{1}{\dfrac{increased\ product}{unit\ carrier\ mass\ flow}}}$$

But also Other Ways

Technical

Reduce Commodities of Energy Transport and Conversion Chain
- Higher conversion efficiency
- Higher energy density of conversion equipment
- Higher energy density of energy carriers
- Higher energy fluxes through conduits

Reduce Ancillary Equipment Needed to Assure Reliable and Safe execution of the main energy transport/energy conversion chain
- Simplify
- Employ innate processes

Institutional

- Standardization (Reduce Engineering Costs)
- License Design in supplier state (Reduce Safety Review Costs)
- Multi-Unit Sites (Reduce permitting costs)

Reduce Financing Costs
- Reduce Risk to Lender/Equity Owner (reduce risk premium on cost of financing)

STAR Seeks to Lower EOS Curve by All Three Methods

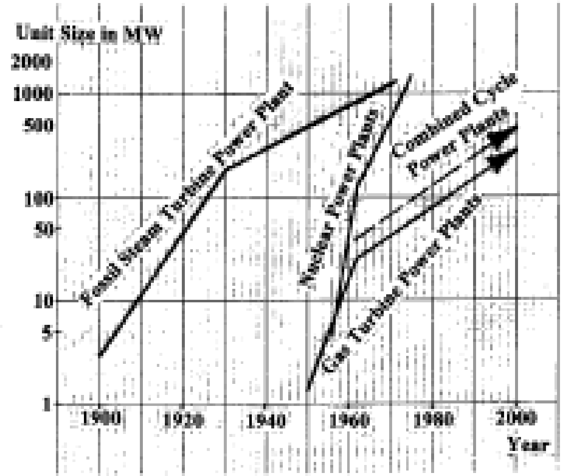
Innovative Technology	LWR		STAR
	Pressurized Water	→	Ambient pressure liquid metal
	~325°C	→	~550°C
	Saturated Rankine Cycle	→	Brayton Cycle
Simplification to Reduce Ancillary Systems	Forced Circulation	→	Natural Circulation
	Active and Passive Safety Systems	→	Same
	Classical Containment (high V/S containment)	→	Preclude HCDA's by intrinsic means permits (high S/V containment)
Reduce Administrative and Financing Costs (reduce uncertainty and financial risk)	Standardization	→	Same
	Licensed Design in Country of Origin	→	Same
	Some Safety Functions in BOP	→	No nuclear safety function for Balance of Plant
	Onsite Construction	→	Factory Fab + Onsite Assembly

EOS Sizing of the Converter Node

The Converter Node

Steam Turbines

- Limited by Liquid Content of Steam @ Last Stage
  - i.e., back pressure should be reduced
  - Therefore annular flow area should be increased
  - Therefore casing diameter should be increased
  - Cost of casing ~ surface area
  - A surface/volume minimization ~ 1/diam. of casing $\overset{\text{EOS driver to}}{\Rightarrow}$ large scale
- Steam Turbines Have Peaked Out at ~1000 - 1400 MW_e

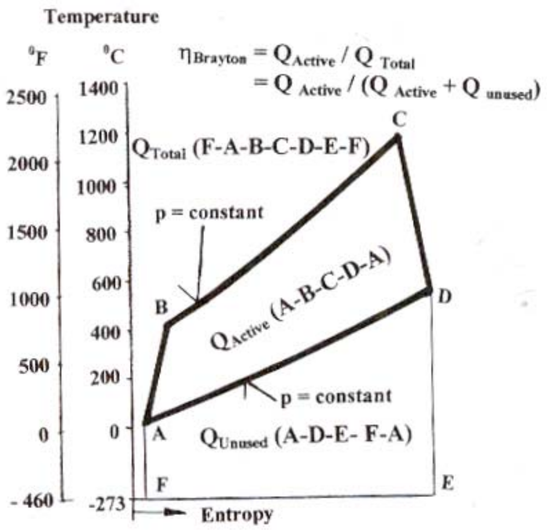


The Converter Node: (Cont.d')

	Units of 10^{-3} gm/cc		
He	11.6	@	7 MPa
N_2	11.6	@	7 MPa
Xe	385.0	@	7 MPa
Ar	116.2	@	7 MPa
S-CO_2	120.0	@	19 MPa
Saturated Steam	36.1	@	6.7 MPa
Liquid Water	1000.0	@	STP

Gas Turbines

- Gas Turbines use a low density working fluid and ambient back pressure
  - Which limits the enthalpy change available across the turbine
  - Increase density by compression – but pdV work of compression is large for gas
  - Improvements have focused on increases in pressure ratio (up to 17:1) which requires temperature increases (up to 1300°C to get more enthalpy into the working fluid at the turbine entrance

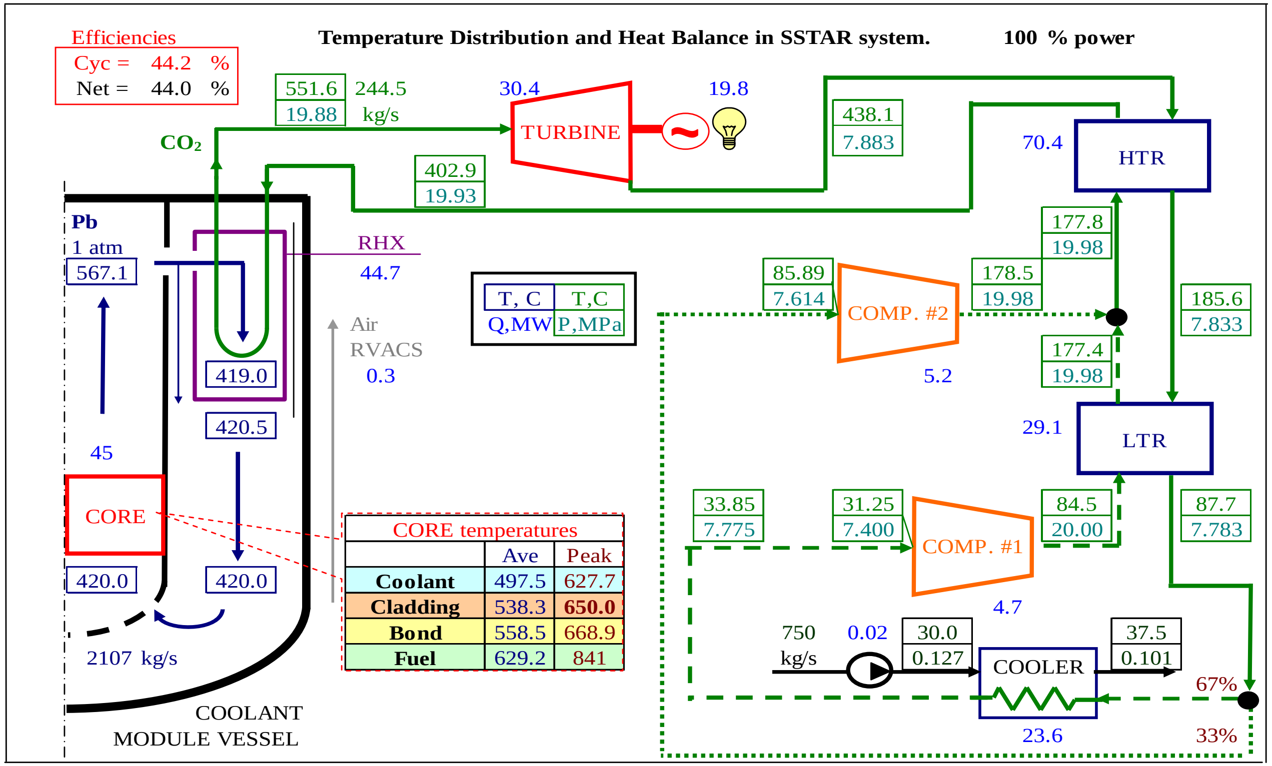


- Power Ratings have peaked out at 250 – 350 MW_e
- Historically for LWR's & LMR's, temperature limits dictate Rankine Steam Cycles
  - LWR's at 325°C : Saturated Cycle
  - LMR's at 500°C : Superheated Cycle

} Large size for EOS

Technology Innovation: Feher Supercritical CO_2 Brayton Cycle

- Achieves ~ 43-44% Conversion Efficiency @ ~500 - 550°C
  - Compression done just above critical point of ~31°C/7 MPa (very high density reduces pdv work of compression)



CORE temperatures

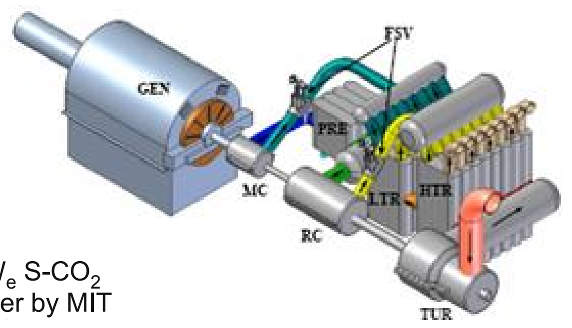
	Ave	Peak
Coolant	497.5	627.7
Cladding	538.3	**650.0**
Bond	558.5	668.9
Fuel	629.2	841

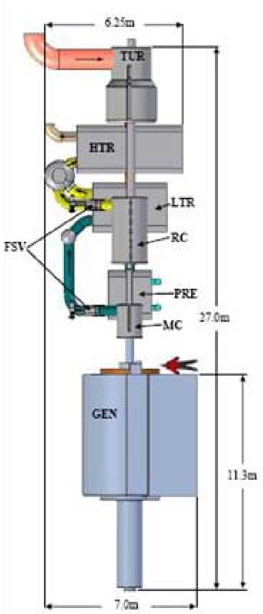
- Note: The increase in conversion efficiency <u>reduces</u> all upstream mass flows and heat requirements

S-CO_2 Brayton Cycle

- High density (compared to ideal gases) makes turbomachinery extremely small

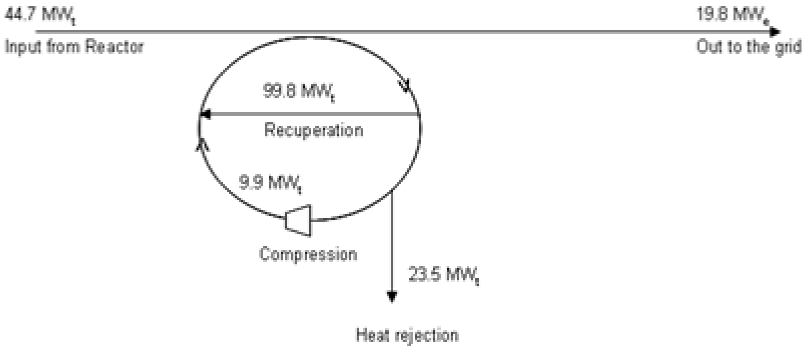
	Units of 10^{-3} gm/cc		
He	11.6	@	7 MPa
N_2	11.6	@	7 MPa
Xe	385.0	@	7 MPa
Ar	116.2	@	7 MPa
S-CO_2	120.0	@	19 MPa
Saturated Steam	36.1	@	6.7 MPa
Liquid Water	1000.0	@	STP





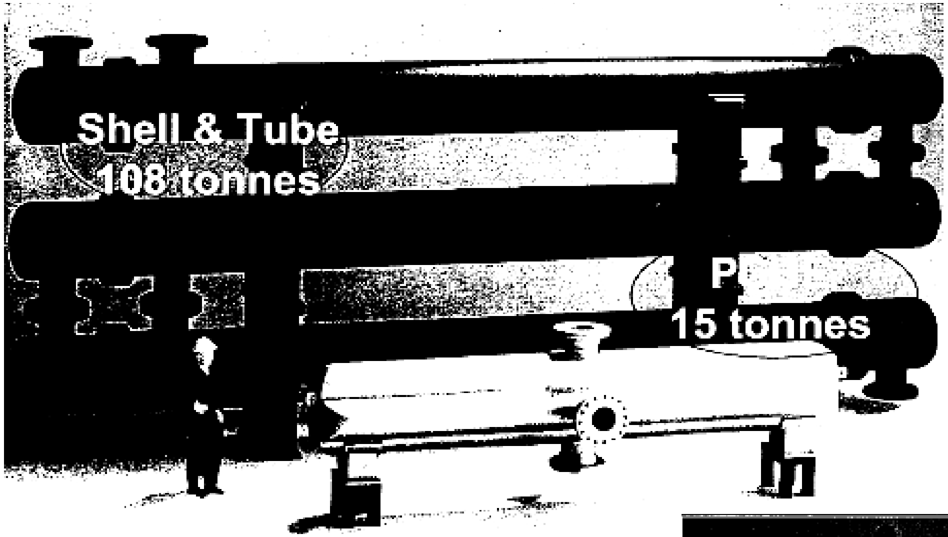
150 MW$_e$ S-CO_2 Converter by MIT

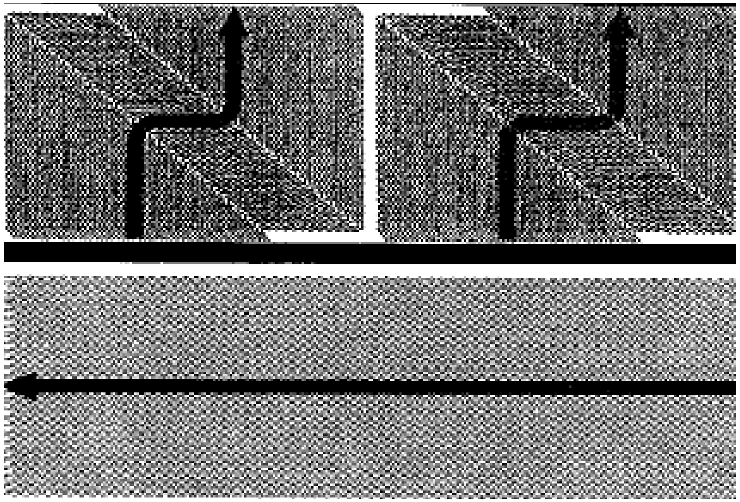
- The cycle is highly recuperated (SSTAR example)



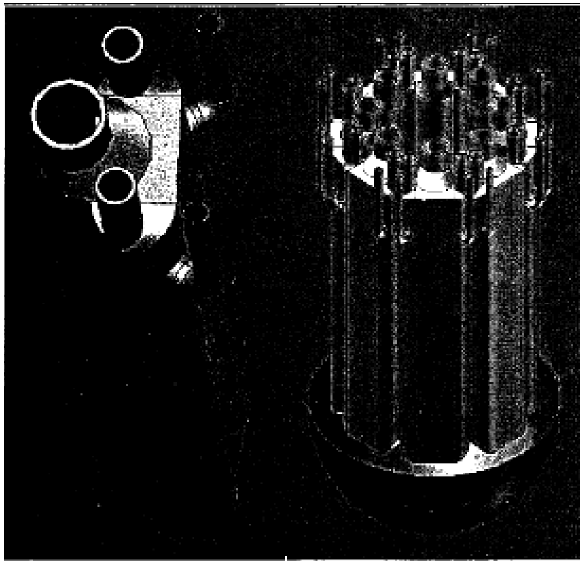
  - On the one hand
    - *A thermal buffer shields reactor from grid disturbances* ⟹ *eliminate intermediate loop even for use on weak, fluctuating grids and for load follow*
  - On the other hand
    - *Expense of heat exchanger*

Another Innovation: Printed Circuit Heat Exchangers





- Power densities can be as much as 50 x that of a standard Tube/Shell HX



- Manufacturing limit on lithographic etching of plates necessitates replication strategy for the recuperator

(Courtesy of Hetric a division of Meggitt PLC)

The Converter Node: Summary

- We move to a different EOS curve for the converter
  - LWR @ 325°C Temperature

    ⇨ *Saturated Rankine Steam Cycle*

    ⇨ *Steam Turbine EOS Technology Peaks out at 1000 – 1400* MW_e

    ⇨ $\eta = 0.33$

  - STAR @ 550°C

    ⇨ *Feher* $S\text{-}CO_2$ *Brayton Cycle*

    ⇨ *Gas Turbine EOS Technology peaks out at size range of interest ~250-350* MW_e

    ⇨ $\eta = 0.44$

  - Significant Payoff

    ⇨ $\frac{44}{33}-1\rightarrow 33\%$ *reduced reactor power for same electrical output*

    ⇨ *Compact equipment; small footprint*

    ⇨ *Small equipment count (simplicity, fewer ancillary systems)*

EOS Sizing The Heat Transport Link

The Heat Transport Link

- Number of Heat Transport Loops Determined by:
  - $Cp\,\Delta T\ \dfrac{MW_t}{kg/\sec}$ *energy density of the carrier*
  - $\left(Cp\,\Delta T\,\rho\ \dfrac{MW_t}{m^3/\sec}\right) * \left(pipe\,area, m^2\right) * \left(flow\,velocity, \dfrac{m}{\sec}\right)$ *specific energy of the carrier*

	Water in LWR	Na in LMR	Pb in LMR	S-CO$_2$ in LMR
$Cp\left(\dfrac{MW\sec_t}{kg°C}\right)$	$6.77\cdot10^{-3}$	$1.25\cdot10^{-3}$	$0.16\cdot10^{-3}$	$1.24\cdot10^{-3}$
$\rho\left(kg/m^3\right)$	670.3	815.4	10,268.8	120.0
$\Delta T\ (°C)$	35	150	150	150
$Cp\Delta T\ \ MW_t/kg/\sec$	0.237	0.188	0.023	0.186
$\left(Cp\Delta T\right)^{-1}\ \dfrac{kg/\sec}{MW_t}$	4.22	5.32	43.48	5.38
$Cp\Delta T\ \ \rho\left(\dfrac{MW_t}{m^3/\sec}\right)$	158.9	153.3	236.2	22.3

The Heat Transport Link (Cont'd.)

- Observations:
  - Water and S-CO_2 require similar mass flows $\left(\frac{kg/sec}{MW_t}\right)$ in the loop between reactor and converter
  - i.e., enthalpy content (energy density) of the carriers are similar

But

  - S-CO_2 has a much inferior density (5½ times less)
- Given a 1 meter ID pipe
  - 400 MW_t can be delivered by S-CO_2 at V = 22.8 m/sec
    2,300 MW_t can be delivered by water at V = 22.8 m/sec
- Therefore
  - $\left.\begin{array}{l}\text{Bigger pipes, or}\\ \text{Higher Velocity, or}\\ \text{More Loops}\end{array}\right\}$ per MWt are needed for the S-CO_2 loop
- Using currently available 20 inch ID (2 inch wall thickness) high temp/pressure pipe
  - Need 2 S-CO_2 loops to deliver 400 MW_t
  - For simplicity, we wouldn't want more than 2

The Heat Transport Link: Summary

- Liquid water and S-CO_2 possess similar energy density $\left(\frac{MW_t}{kg/\sec}\right)$

But

- (Liquid) water is much superior to (gaseous) S-CO_2 on specific energy $\left(\frac{MW_t}{m^3/\sec}\right)$

Given a goal to achieve simplicity by limiting loops to $\leq$ 2

- LWR's using water match nicely with

  Steam Turbines that max out at ~1000 MW_e

- STAR's using S-CO_2 match nicely with

  Feher Brayton Cycle sized at ~200 MW_e

EOS Sizing The Nuclear Converter Node

The Nuclear Reactor Energy Converter Node

- Design Goals for Reactor Differ

LWR: Maximize heat output per unit vessel size consistent with safety

STAR: Maximize heat output from a rail-shippable vessel consistent with
  - * natural circulation
  - * 20y refueling interval
  - * passive safety

- For STAR
  - *Derate the power density (for 20y refueling)*
  - *Use large diameter fuel pins*

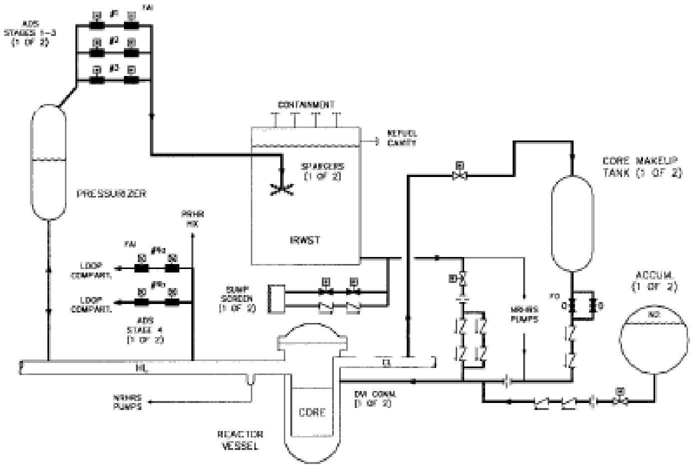
  and
  - *Open the lattice (for natural circulation)*
  - We can remove only 400 MW_t by natural circulation in a rail shippable vessel size

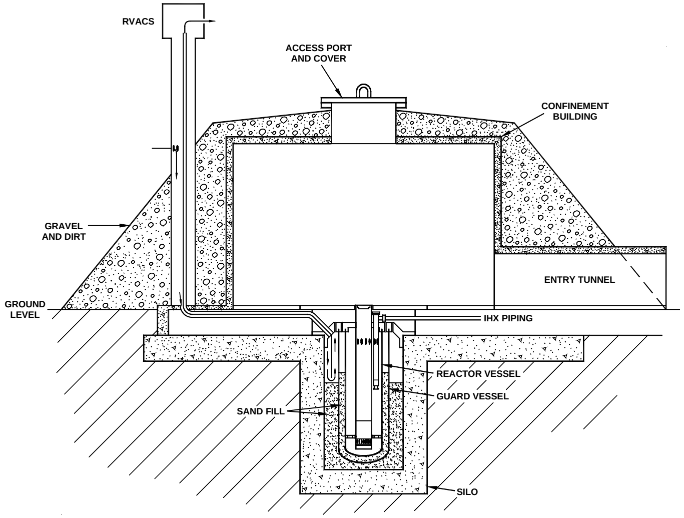
- Vessel sizes are similar
  - AP-1000 4.4m OD x 12m high x 20 cm thick
  - STAR 5.5m OD x 16.9m high x 5.1 cm thick
  - m^3 steel/MW_e – Approximate
    - *AP1000 ~ 0.012* m^3/MW_e
    - *STAR ~ 0.041* m^3/MW_e
  - m^3 concrete structures around vessel/MW_e
    - *? (but STAR is clearly worst)*
- Containment sizes are very different

  (see next page)

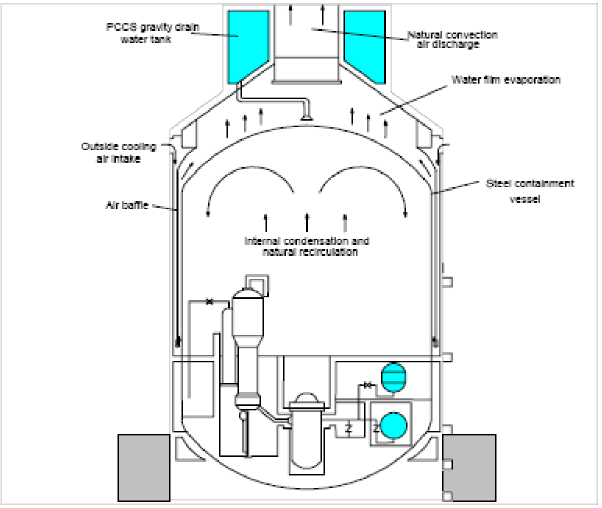
Ancillary Structures for Nuclear Reactor Converter Node

Decay Heat Removal





Containment & Shield



STAR containment is comprised of guard vessel + dome ~ 6m x 18m ~ 2.8 m^3/MW_e

Shield is

- silo emplacement, dirt/gravel bunker

AP1000

Steel Containment is:

39.6m diam x 65.6m high ~ 67 m^3/MW_e

Concrete shield building is: Bigger still

EOS Sizing The Nuclear Fuel/Spent Fuel Return Loop

The Fuel Supply/Spent Fuel Return Loop

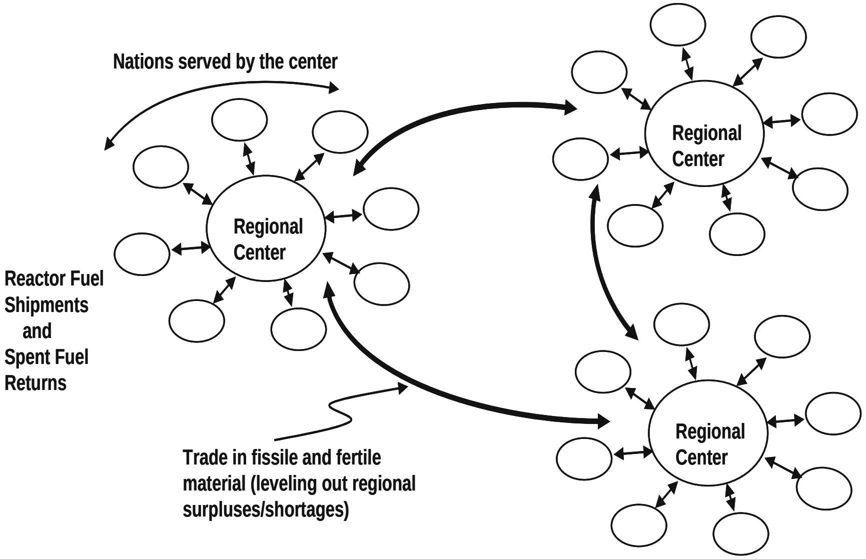
- Average Discharge Burnups expressed as kg/sec mass flow

$$\frac{kg\,fuel/\sec}{MW_e} = \frac{1}{discharge\,burnup\,\frac{MW_t d}{kg}} * \frac{1}{\eta} * \frac{1}{60*60*24\,\frac{\sec}{d}}$$

	$\frac{MW_t\,days}{kg\ Heavy\ Metal}$	Refueling Interval	#Fuel Batches in Core
LWR	40-50	12-18 months	3-4
LMR	100-120	12 months	3-4
STAR	80-100	15-20 years	1

LWR	$\frac{1}{50}\ \frac{1}{.33}\ \frac{1}{86,400} = 0.701 \times 10^{-6}\ \frac{kg/sec}{MW_e}$
LMR	$\frac{1}{110}\ \frac{1}{.39}\ \frac{1}{86,400} = 0.269 \times 10^{-6}\ \frac{kg/sec}{MW_e}$
STAR	$\frac{1}{80}\ \frac{1}{.44}\ \frac{1}{86,400} = 0.328 \times 10^{-6}\ \frac{kg/sec}{MW_e}$

- The incredible energy density of nuclear fuel facilitates a new architecture for Energy Supply
  - 20 years of energy securely stored in-reactor on sovereign territory
  - No more than a dozen fuel cycle centers to service entire world energy needs

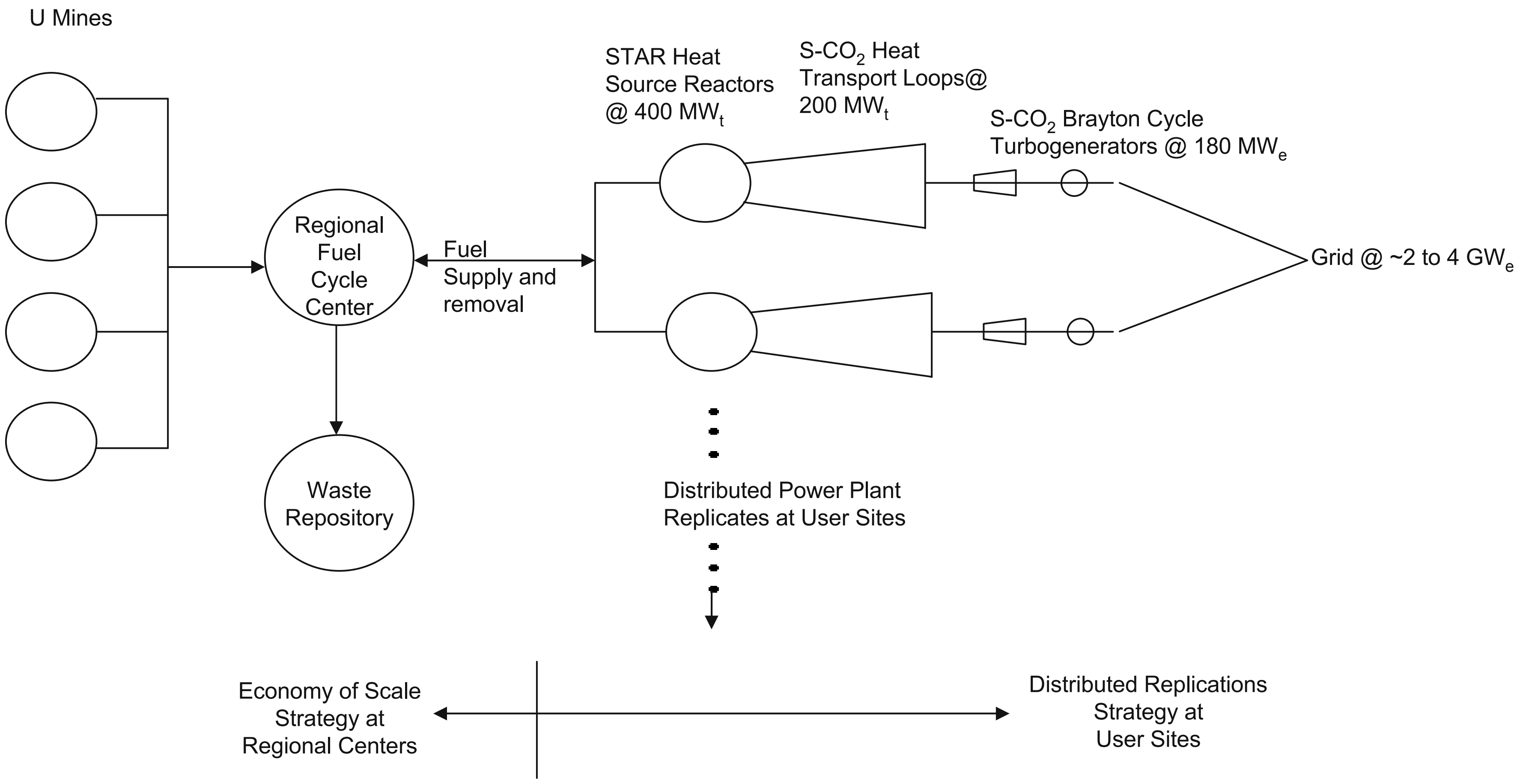


Optimizing of Overall Architecture

Optimizing EOS for The Entire STAR Energy Delivery Chain

- The target size is $\lesssim$ 200 MW_e to meet the needs of a substantial market segment
- Working backwards along the links and nodes we encounter several pinch points
  - Gas turbine plants peak out at ~250 – 350 MW_e
  - S-CO2 heat transport loops can carry ~200 MW_t in commercially available pipes
  - To achieve natural circulation in a rail shippable vessel size limits power to $\lesssim$ 400 MW_t
  - Passive (RVACS) decay heat removal works only for power $\lesssim$ 1000 MW_t
  - To achieve 20y refueling interval with zero burnup reactivity loss in a rail shippable vessel size with natural circulation limits ave burnup to ~ 80 – 85 MW_td/kg HM
- These minima in the individual EOS curves of links and nodes line up nicely for the 400 MW_t/180 MW_e STAR-LM

The STAR Energy Supply Architecture



U Mines

STAR Heat Source Reactors @ 400 MW_t

S-CO_2 Heat Transport Loops@ 200 MW_t

S-CO_2 Brayton Cycle Turbogenerators @ 180 MW_e

Regional Fuel Cycle Center

Fuel Supply and removal

Grid @ ~2 to 4 GW_e

Waste Repository

Distributed Power Plant Replicates at User Sites

Economy of Scale Strategy at Regional Centers

Distributed Replications Strategy at User Sites

Does the STAR EOS Curve Lie Below the Projection of the LWR Curve Down to the Small Reactor Range?

- We don’t know yet!
- We think it is Plausible because:
  - The S-CO_2 Brayton Cycle
    - *May max out at ~200 - 300 MW_e (the same as other gas turbines)*
    - *Reactor power rating is reduced by 1/3 for the same electricity*
    - *High density of S-CO_2 ⇨ very small turbomachines occupies a small footprint*
  - The Heat Source (400 MW_t) reactor is the maximum feasible in a rail shippable vessel (given the requirements of natural circulation and 20y refueling interval and passive safety)
    - *Has no pumps*
    - *Has a simplified control system (passive load follow)*
    - *Has a small (high surf/vol ratio) containment and shielding buildings (much reduced commodities)*
    - *Assigns no safety function to the Balance of Plant (much reduced construction cost)*
  - The fuel discharge burnup
    - *Is 60% higher per MW_t*
    - *Is 80% higher per MW_e*