G4-ECONS: A Model for Calculating the Levelized Unit Electricity Cost (LUEC) for Advanced Nuclear Systems

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Gen IV EMWG Products and Applications

Background

Products

- Cost Estimating Guidelines
- G4-ECONS 1.0 Software
- Software Users Manual (Detailed)
- Software Users Guide (Summary level)

Application Examples

- JAEA Sodium Fast Reactor (JSFR)
- Modular Pebble-bed Reactor (MPBR)

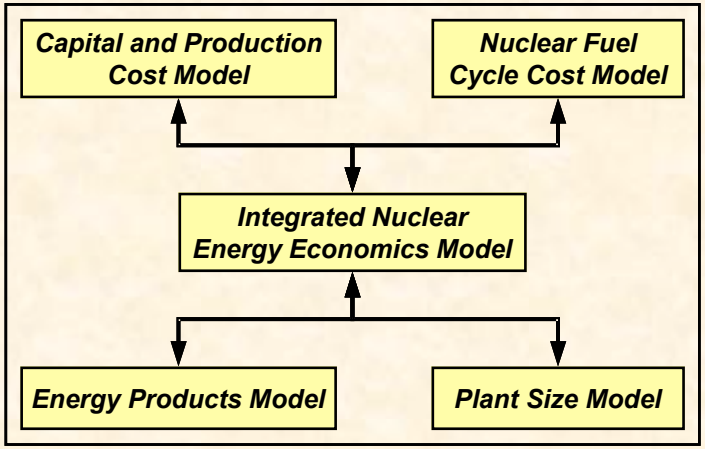
Background

- EMWG Charter
- EMWG History
- EMWG Members

EMWG Charter

Develop economic models for evaluation of Gen IV systems with respect to goals established by GIF

- **Establish and execute plan to develop an integrated model and its constituent models**
  - Capital/production cost model
  - Nuclear fuel cycle cost model
  - Plant size model
  - Energy products model
    - Electricity
    - Hydrogen
    - Desalination
    - Actinide burning



- **Provide the models, documentation, and other economic information to all GIF organizational entities**
- **Report to Experts' Group on progress and work plans**

EMWG History

- Began formation in October 2002
- First meeting held February 2003
- Meeting 4 times per year since
- Added members over the next 3 years
- Work plans and products have been submitted to the Experts Group annually

EMWG Members

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Products

- GIF Cost Estimating Guidelines, Rev. 2
  - Provides guidance for consistent, transparent cost estimates for Gen IV systems
  - Based on a Code of Accounts approach for estimate completeness and transparency
  - Allows for "top down" to "bottom up" approach depending upon available design detail
  - Provides a "level playing field" for future evaluation

Products

- G4-ECONS 1.0 (EXCEL Calculation of Nuclear Systems)
  - An EXCEL based software tool to facilitate the implementation of the Cost Estimating Guidelines
  - Version 1.0 provides cost estimation capabilities for reactor plants producing electricity
  - Future versions are intended to allow cost estimation of complete energy systems including fuel cycle facilities
  - Levelized unit costs for electricity and other products are major economic figures-of-merit (e.g. $/Mwh, $/kgH2, $/m3 of potable water)

Products

- **Users Manual**
  - Provides detailed guidance to the user for fuel cycle selection and overall data input
- **Users Guide**
  - Provides simplified guidance to the experienced or casual user

Application Examples

- Test Applications During Development
  - CE System 80+ PWR
  - Modular GCR
  - DOE AFCI/GNEP use for fuel cycle cost estimates
- Test Applications for Version 1.0
  - CE System 80+ for benchmarking
  - JSFR for Gen IV demonstration and benchmarking

G4-ECONS Calculations

- Sums all subsystem costs (direct costs) and indirect costs (including design and licensing) into an "overnight" cost
- All subsystem costs organized by Gen IV Code of Accounts, which is derived from older IAEA and EEDB Codes of Accounts
- Construction cumulative expenditure pattern (S-curve) applied to "overnight cost" to calculate interest during construction (IDC)
- First core and startup can be included in "overnight" cost
- Sum of "overnight cost" and IDC is "total capital cost," which is then "amortized" over operating life of plant
- Annual operating costs also organized by Code of Accounts
- Annual fuel cycle cost calculated from unit costs for various front-end and back-end steps and the overall fuel cycle material balance

G4-ECONS Calculations (cont.)

- Decontamination and decommissioning annualized by use of an "escrow fund," which sets aside funds annually to accumulate lump sum D&D amount at end-of-life
- Plant electrical output is assumed constant over life of plant and its calculation assumes use of an average annual capacity factor
- A fixed charge rate is calculated for amortization of capital. It depends on plant life and the real discount rate.
- From the annual electricity production and annual cost components, the following levelized unit cost components are calculated in mills/kwh (or $/Mwh) and summed to produce the total LUEC:
  - Capital
  - O&M
  - Fuel cycle (front-end and back-end)
  - D&D

G4-ECONS Sample Fuel Cycle Calculation

Fuel Cycle Code = 1	10/6/2006	OPEN CYCLE	Case: Sys80+ PWR using LEUO2 (repository disp of spent fuel) BASE

Fuel Assy description: UOX-PWR

DISPLAY ONLY: DO NOT CHANGE THESE VALUES MANUALLY !!!

prod enr: 3.78% % U-235
prod kgU/Year 29,628

Energy/Year = 9.11E+09 kwh
Capacity Fact = 80.0%
Burnup 38,824 Mwd/MTHM

Mine and Mill
UC ($/kgU) 31.20
Mill prod in kgU/Year as U3O8 = 250,867
lb U3O8 = 652,329
$/lb U3O8 = 12
$M/Year = 7.83

U3O8 to UF6 Conversion
UC ($/kgU) = 6.00
Feed kg U/Year 250,867
Feed Assay = 0.711 % U-235
$M/Year = 1.51

Enrichment
Ann SWU = 144,047
UC ($/SWU) 100.00
$M/Year = 14.40
Tails Assay: 0.3 %U-235
Tails kgU/Year = 221,239

DUF6 Conversion and Disposal
UC ($/kgU) 0.00
$M/Year = 0.00

Tails Assay Optimizer: OFF

Fuel Fabrication
Feed: kgU/Year 29,628
UC ($/kgU) 180.00
$M/Year = $5.33

Reactor
Type: Sys80+ PWR using LEUO2 (repository disp of spent fuel) BASE
Power in Mwe 1300
kgU/FA 426
Fas/Year = 69.6
kgU/Year = 29,628
$/FA = 417,987

Equilibrium Reloads Only		
	Front end $M/Year =	29.07
	Front end $/kgU =	981
	Front end mills/kwh =	3.19
	(Fuel Cycle Component of LUEC)	

FUEL CYCLE AT A GLANCE
Based on Equilibrium Reloads on an Annual Basis
All streams and costs are annualized regardless of cycle length

Annual rate (kgHM/Year) 29,628
Assemblies/Year 69.6

Packaging and storage outside reactor building (incl transport if off reactor site)
Unit Cost ($/MTHM) 0.00

$M/Year 0.00

Transportation to and emplacement in Geologic Repository
UC (mls/kwh) 307.50

$M/Year = 2801.45
$/kgHM equiv 308
Repos cost basis MTHM

Equilibrium Reloads Only		
	Back end $M/Year =	9.11
	Back end $/kgHM =	307.5
	Back end mills/kwh =	1.00
	(Fuel Cycle Component of LUEC)	

Equilibrium Reloads Only		mills/kwh
	Fuel Cycle - Front End	3.19
	Fuel Cycle - Back End	1.00
	TOTAL Fuel Cycle	4.19

First Core Contributions Not Included

G4 ECONS Version 1.0

Output of G4-ECONS (PWR Example)

G4 ECONS Version 1.0

Case: **Sys80+ PWR using LEUO2 (repository disp of spent fuel) BASE**

Strategy 1

Worksheet name: LUEC Summary

Total Reactor and Fuel Cycle System

Summary of Model Results

Discount Rate = 5.00%

	Annualized Cost in $M/Year	Mills/kwh or $/MWh
Capital (Including 1st Core and Financing)	158.52	17.40
Operations Cost	78.47	8.61
Fuel Cycle - Front End	29.07	3.19
Fuel Cycle - Back End	9.90	1.09
D&D Sinking Fund	2.48	0.27
TOTAL LUEC	**278.44**	**30.56**

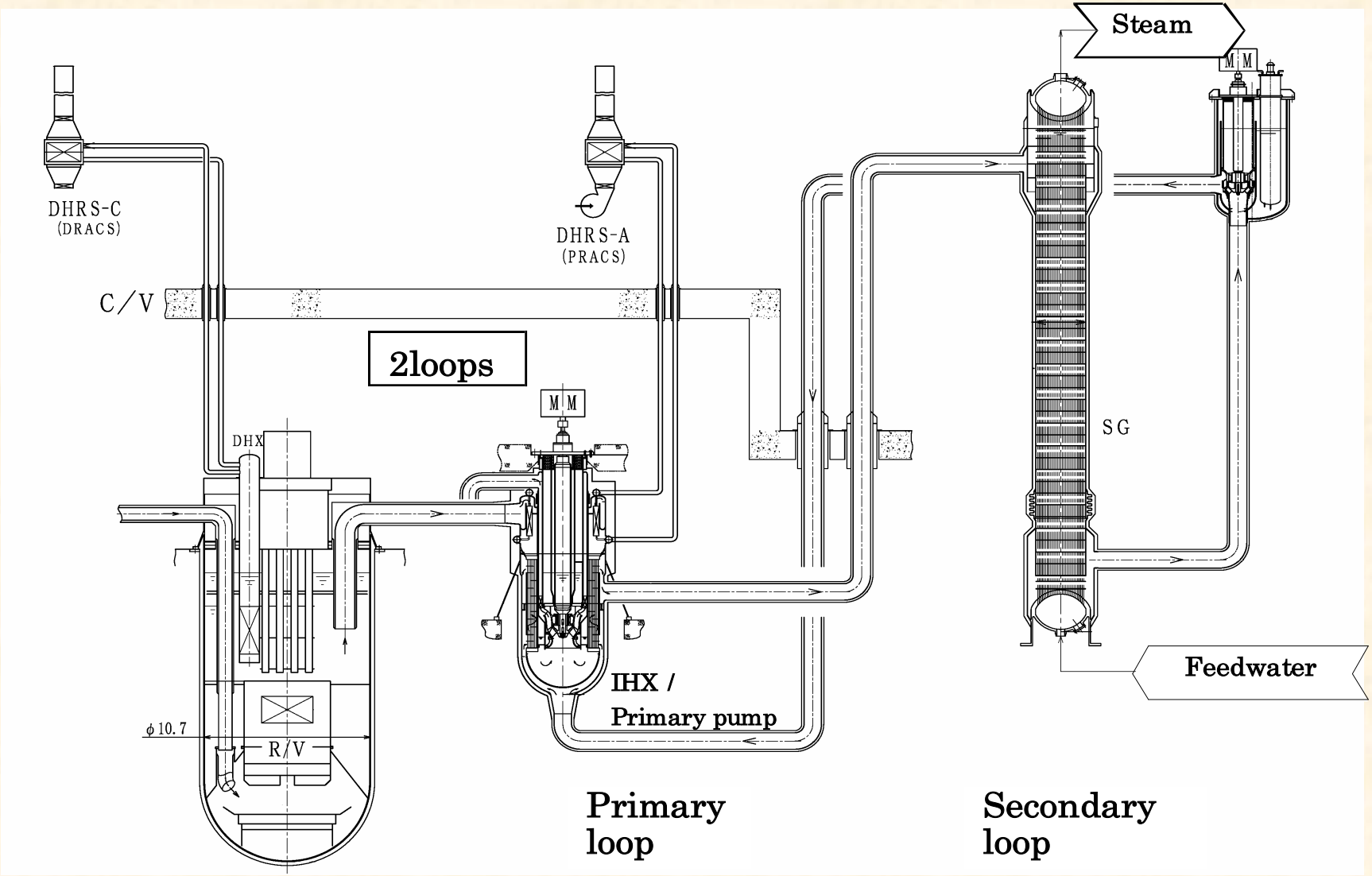
G4-ECONS Attributes

- Transparency—All EXCEL algorithms and cells are visible
- Simplicity—Calculated costs, electricity production, and fuel cycle are annualized (appropriate for comparing technologies)
- Universality—Discount rate is only major financial parameter (model not specific to one nation, type of economy, or taxation structure)
- Linkability—Cells can be linked to cost-scaling equations and reactor design parameters, thus G4-ECONS can be used for optimization

JSFR Application

- JAEA Sodium Fast Reactor
  - Brief description of JSFR
  - JAEA economic estimation with full recycle
  - G4-ECONS 1.0 economic estimation
  - Comparison

JSFR


Steam
M M
DHRS-C
(DRACS)
DHRS-A
(PRACS)
C/V
2loops
M M
DHX
SG
IHX /
Primary pump
Feedwater
φ10.7
R/V
Primary
loop
Secondary
loop

JSFR

Items	Specifications
Reactor type	Sodium-cooled loop type reactor
Electricity output	1500 MWe
Thermal output	3530 MWt
Number of primary loops	2
Primary sodium temperature	550℃ / 395℃
Secondary sodium temperature	520℃ / 335℃
Main steam temperature / Pressure	495℃ / 18.7 MPa
Feed water temperature / Flow rate	240℃ / 5.8×10^{3} t/h
Plant efficiency	Approx. 43%
Fuel type	MOX
Burnup (driver fuel discharge average)	150 GWd/t
Breeding ratio	over 1.1
Operation cycle length	over 18 months

JAEA Cost Estimation

- Performed as part of a feasibility study begun in 1999
- Capital cost estimated using command cost code (CCC)
- Fuel cycle cost estimated by NEA methodology
- Levelized unit generation cost calculated by FCC-EX code

JSFR G4-ECONS 1.0 Analysis

- Performed by JAEA and colleagues
- G4-ECONS used for all elements of estimate
- Input data from previous economic studies used

JSFR G4-ECONS 1.0 Analysis

- Documented in report: "Sample Calculation of G4-ECONS Code on the JAEA Sodium Cooled Fast Reactor (JSFR) System"
- Reviewed by EMWG through several iterations

JSFR G4-ECONS 1.0 Results

case: **JSFR Sample Calculation/ April 14,2006 (Closed cycle)**

Worksheet name: LUEC SUMMARY

TOTAL REACTOR & FUEL CYCLE SYSTEM

Summary of Model Results			
Case:	**JSFR Sample Calculation/ April 14,2006 (Closed cycle)**		
	Discount rate=	2.00%	
		Annualized Cost in $M/yr	Mills/kwh or $/MWh
	Capital Cost incl Financing	$77.4	6.51
	Operations Cost	$88.1	7.41
	Fuel Cycle Cost	$77.8	6.55
	D&D Cost	$5.1	0.43
	Totals	$248.5	**20.90**

Model Shows That Financial Factors Strongly Impact Costs

(The interest during construction for capital cost, the sinking fund interest for D&D cost, and fuel cycle cost are changing.)

Plant economic life: 40 years	Mills/kWh or $/MWh		
	2%	5%	10%
Capital Cost incl. Financing	8.272	14.823	33.112
Operations Cost	7.414	8.113	9.531
Fuel Cycle Cost	6.677	7.158	8.475
D&D Cost	0.817	0.408	0.111
Totals	23.180	30.503	51.229

Plant economic life: 60 years	Mills/kWh or $/MWh		
	2%	5%	10%
Capital Cost incl. Financing	6.509	13.437	32.487
Operations Cost	7.414	8.113	9.531
Fuel Cycle Cost	6.547	7.018	8.308
D&D Cost	0.432	0.139	0.016
Totals	20.903	28.707	50.342

Comparison of Model Results

Mills/kWh or $/MWh	G4-ECONS Code	FCC-EX*1	Final Report of the FS Phase-2
Estimated year (year)	2005	2005	2005
Capital Cost incl. Financing	6.076	5.944	6.441
D&D Cost	0.432	0.432	0.432
Operations Cost	7.414	7.282	7.308
Front-End Fuel Cycle	1.460	1.460	1.499
Back-End Fuel Cycle	5.087	5.087	2.994
First Core Fuel Front-End Cost*2	0.433	0.234	0.413
First Core Back-End Cost*2	-	0.814	0.876
Totals	20.903	21.254	19.964

*1 Each cost is individually indicated for comparison.
*2 In the case of "FCC-EX" and "Final Report of the FS Phase-2," the cost of initial core fuel is counted as a fuel cycle cost. However, in the G4-ECONS Code of EMWG, its front-end cost (0.0477yen/kWh) is considered as a capital cost and its backend cost (0.0897yen/kWh) is not accounted.

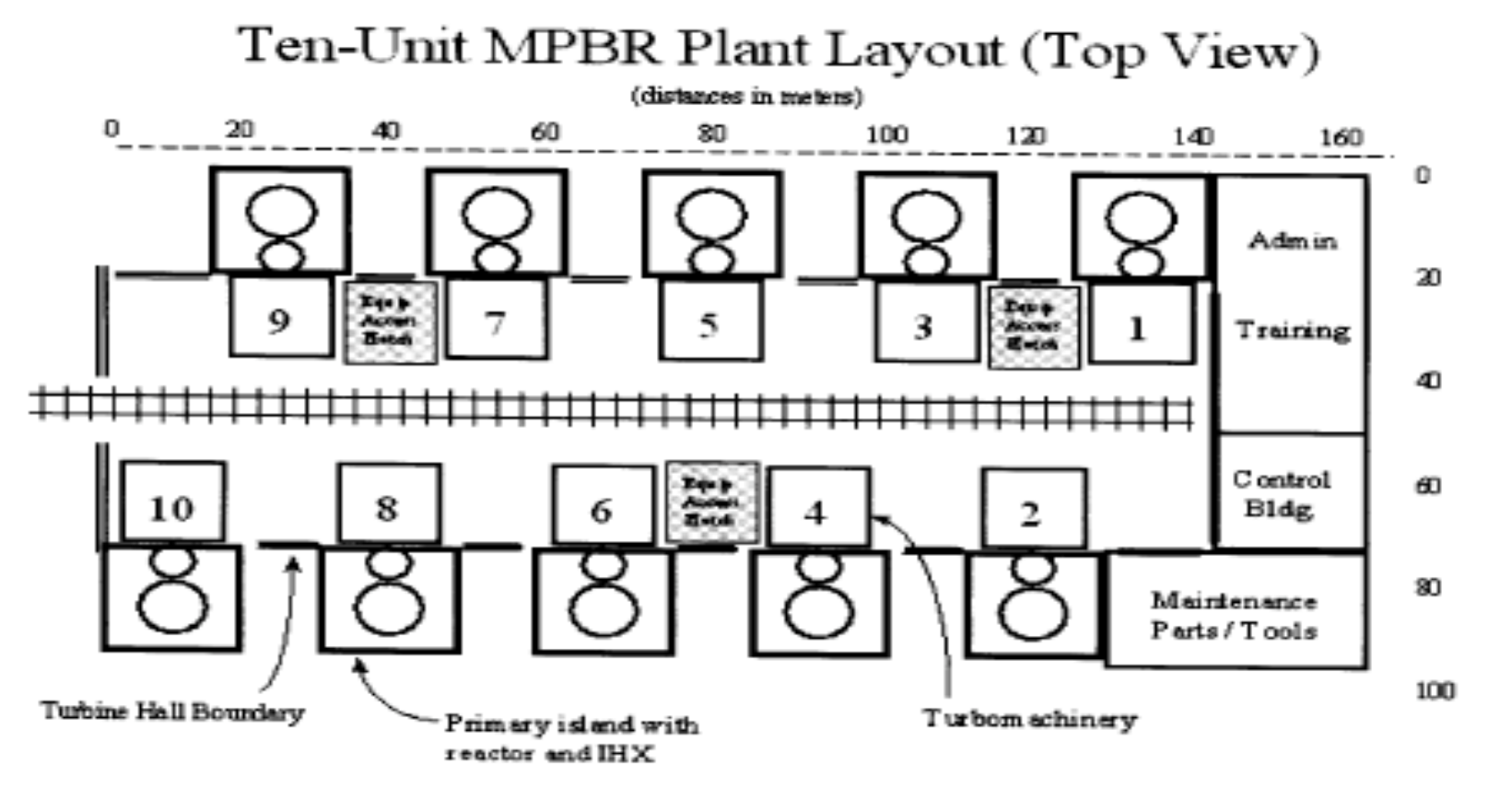
Comparison (cont.)

Mills/kWh or $/MWh	Gen IV G4-ECONS Code (Capital Cost incl. Financing)	Final Report of the FS Phase-2 (Capital Cost which doesn't contain D&D Cost)
Capital cost	6.509	6.441
Depreciation	(6.076)	(4.796)
Interest on depreciation residual value (business fee)		(0.967)
Initial core fuel fabrication cost	(0.433)	N A (included in fuel cost)
Fixed assets tax	-	(0.677)

A Modular Reactor Case

- G4-ECONS was used to evaluate a 10-module modular pebble-bed reactor concept described in an MIT presentation
- Costs were revised upward to reflect a change in the estimating constant-dollar base year from 1992 to 2001
- Fuel fabrication costs were revised upward to better reflect TRISO fuel experience
- Amortization of "factory" assumed to be imbedded in reactor cost

10-Module MPBR (MIT Design)
[110 MW(e)@ x 10 Reactors → 110 MW(e)]



Sample Format of MPBR Capital Cost Data Available from MIT Presentation

MPBR PLANT CAPITAL COST ESTIMATE
(MILLIONS OF JAN. 1992 DOLLAR WITHOUT CONTINGENCY)

Account No.	Account Description	Cost Estimate
20	LAND & LAND RIGHTS	2.5
21	STRUCTURES & IMPROVEMENTS	192
22	REACTOR PLANT EQUIPMENT	628
23	TURBINE PLANT EQUIPMENT	316
24	ELECTRIC PLANT EQUIPMENT	64
25	MISCELLANEOUS PLANT EQUIPMENT	48
26	HEAT REJECT. SYSTEM	25
	TOTAL DIRECT COSTS	1,275
91	CONSTRUCTION SERVICE	111
92	HOME OFFICE ENGR. & SERVICE	63
93	FIELD OFFICE SUPV. & SERVICE	54
94	OWNER'S COST	147
	TOTAL INDIRECT COST	375
	TOTAL BASE CONSTRUCTION COST	1,650
	CONTINGENCY (M$)	396
	TOTAL OVERNIGHT COST	2,046
	UNIT CAPITAL COST ($/KWe)	1,860
	AFUDC (M$)	250
	TOTAL CAPITAL COST	2296
	FIXED CHARGE RATE	9.47%
	LEVELIZED CAPITAL COST (M$/YEAR)	217

Updated MPBR LUEC (Constant 2001$ and More Realistic Fuel Fabrication Cost*)

G4 ECONS Version 1.0

Case: **10-module PBMR sample calculation BASE**

Strategy 4

Worksheet name: LUEC Summary

Total Reactor and Fuel Cycle System

Summary of Model Results

Discount Rate = 5.00%

	Annualized Cost in $M/Year	Mills/kwh or $/MWh
Capital (Including 1st Core and Financing)	199.46	23.00
Operations Cost	56.42	6.51
Fuel Cycle - Front End	102.88	11.86
Fuel Cycle - Back End	10.31	1.19
D&D Sinking Fund	2.23	0.26
TOTAL LUEC	**371.30**	**42.81**

* **~$90/pebble instead of $24/pebble**

Application

- Quick run through of G4-ECONS input and summary screens (for MPBR Strategy) to be done from computer

The LUEC as an Economic Figure of Merit Does Not "Tell the Whole Story"

- The "cost" of electricity is not the same as the "price"
- One must know if costs represent "First-of-a-kind" (FOAK) or "Nth-of-a-kind" (NOAK)
- Market considerations are very important
  - SMRs higher LUECs might be competitive in small markets which can't take output of large reactor or use expensive oil-based fossil fuel

Conclusion

- The EMWG product package is available to GIF nations and is capable of providing reasonable cost estimates for Gen IV and Gen III reactors
- The final EMWG product package should be available to GIF by the end of 2007 and will be capable of providing reasonable cost estimates for complete Gen IV systems
- Future training and workshops will be planned if sufficient Gen IV participant interest
- Consideration will be given to non-GIF requests for G4-ECONS