FIRST-WALL BLANKET DESIGN ($R_0 = 2.3$ m)

"Applicable to any high power density fusion system"

Inputs

- Γ_n – Ave/max = 7.99/11.2 MW/m^2
- ϕ_{FW} – Ave/max = 1.94/2.68 MW/m^2
- Geometry
- Neutronics results
- He at 15 MPa
- T_{in} = 250°C
- T_{out} = 650°C
- He, Li Pb, V-alloy properties
- Nested shell geometry

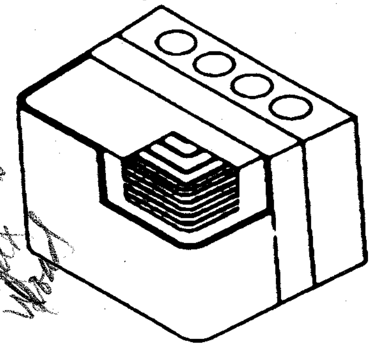
Design Criteria

- V–T_{max} < 700°C
- LiPb–T_{max} < 1000°C
- $V_{He} < \frac{1}{3}$ sonic speed
- $V_{He} \ll V_{critical\ vibration}$
- Primary and secondary stresses (simple tube)

Design

(A nest shell poloidal module)

- He–cooled, V-alloy, LiPb breeder*
- First wall, blanket



Results

- Design Criteria met.

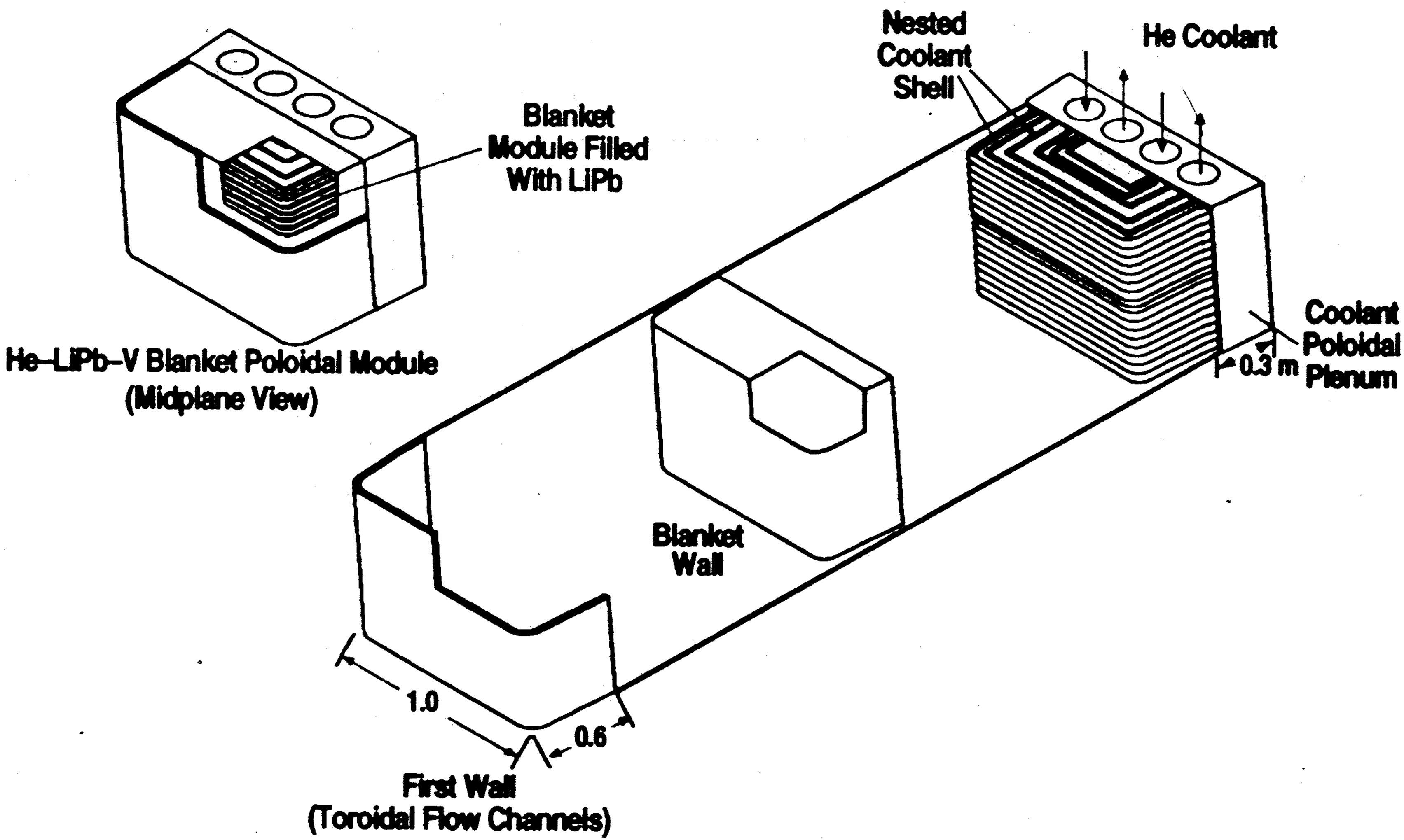
Tube	Diameter	Wall Thickness
FW, mm	8	2
Blanket, mm	10	1.5

- Layer by layer volume fractions generated for neutronics iteration (Average volume fractions –V-alloy 15%, LiPb – 65%)
- η_{Th} – 45%
- 1-D TBR = 1.2 (90% ^{6}Li)

* Compatibility issue of He-impurites (O_2, H_2) with V-alloy not addressed

228-97

GENERAL ATOMICS


Blanket
Module Filled
With LiPb
He–LiPb–V Blanket Poloidal Module
(Midplane View)
Nested
Coolant
Shell
He Coolant
Coolant
Poloidal
Plenum
0.3 m
Blanket
Wall
1.0
0.6
First Wall
(Toroidal Flow Channels)

LAR FIRST WALL AND BLANKET PARAMETERS

Plasma aspect ratio, A	1.4
Plasma vertical elongation,	3.0
minor plasma radius, a, (m)	1.65
major toroidal radius, R_o, (m)	2.31
plasma volume, (m^3)	372.42
first-wall surface area, (m^2)	311.9
number of TF coil	12
module mid-plane width, (m)	1.037
module height, (m)	11.59
fusion power density, (MW/m^3)	8.367
fusion power, (MW)	3116
Γn, ave/peak, (MW/m^2)	7.99/11.19
ϕ_{fw}, ave/peak, (MW/m^2)	1.936/2.677
blanket energy multiplication	1.4
Helium pressure, (MPa)	15
Tin, (C)	250
First wall-circular tube:	
inside diameter, mm	8
wall thickness, mm	2

	inlet	middle	outlet
Tin, (C)	250	290	310
coolant velocity, m/s	109.6	115.6	121.6
heat transfer coeff. W/m^2K	14750	14870	14980
Tmax V-alloy, (C)622	652		680
pressure drop first wall, MPa	1.68		
allowable primary stress, MPa	120		
allowable secondary stress, MPa	360		
primary stress, MPa	30		
secondary stress, MPa	203		

First row of blanket tube:	
inside diameter, mm	10
wall thickness, mm	1.5
Tin, (C)	310
Tout, (C)	362
coolant velocity, m/s	45.8
heat transfer coeff. W/m^2K	6215
Tmax V-alloy, (C)	695
Tmax LiPb, (C)	864
pressure drop 1st. blanket tube, MPa	0.058

LOW ASPECT RATIO CONCEPT FOR A FUSION POWER PLANT*

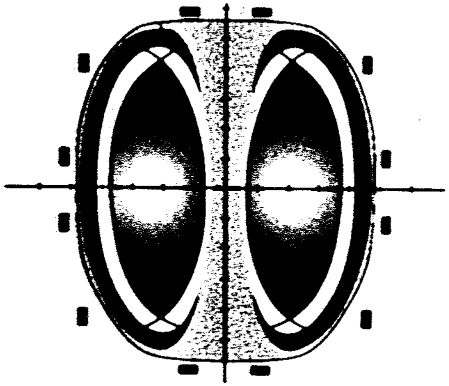
An aggressive design approach

Physics

- 62% β
- 87% BS fraction
- Core radiation

Technology

- Unshield central column
- High Γ_n blanket
- High He pressure CCGT system



by

C.P.C. WONG, R. CERBONE,
E.T. CHENG, R.L. MILLER,
R.D. STAMBAUGH

Presented at
Japan/U.S. Workshop
on Fusion High Power Density Devices and Design
Sendai, Japan

*GA Internal R&D Funds and TSI Research, DOE SBIR program.

OCTOBER 20–22, 1997

LOW ASPECT RATIO CONCEPT FOR A FUSION POWER PLANT

Inputs

GA–LAR physics formalism*

Key Parameters:

- $A = 1.4$
- $\beta_T = 62\%$
- $\kappa = 3$
- BS fraction = 87%
- $Ti = 25$ keV

Design Approach

Optimized by:

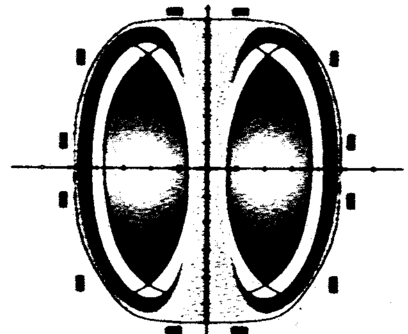
- Approaching technology limits
- Minimizing physical size
- Minimizing recirculating power
- Eliminating inboard shield
- Spreading transport Power to first wall
- Using high power density blanket
- Maintaining low activation goal

Critical Elements Evaluated

- TF–coil central column
- Impurity core radiation
- First–wall blanket design
- COE

Design Code Results

- $R_o = 2.3$ m
- Pe–net: 1092 MW
- COE* = 63.5 mill/kWh†



* Includes central column and blanket replacements

* R. Stambaugh et al, "The Spherical Tokamak Path To Fusion Power," submitted to Fusion Technology

†Coal and APWR: 50–60 mill/kwh beyond the year 2000

228-97

GENERAL ATOMICS

PHYSICS AND ENGINEERING PARAMETERS OF A LAR 1092 MW(e) DESIGN

Plasma aspect ratio, A	1.4
Plasma vertical elongation	3.0
Minor plasma radius, a (m)	1.65
Major toroidal radius, R_0 (m)	2.31
Plasma volume (m^3)	372.42
First-wall surface area (m^2)	311.9
Radial profile exponent for density, s_n	0.25
Radial profile exponent for temperature, s_T	0.25
Toroidal beta (%)	62
Poloidal beta (%)	1.43
On-axis toroidal field (T)	2.5
Plasma current, I (MA)	29.91
Plasma ion temperature (keV)	25
Plasma electron density, n_e ($10^{20}/m^3$)	3.266
Plasma ion density ($10^{20}/m^3$)	1.955
Kr fraction that of n_e (%)	0.12
Effective plasma charge, Z_{eff}	2.87
Fusion power density (MW/m^3)	8.367
Fusion power (MW)	3116
Toroidal field coil summary	
Number of TF coils	12
Mass of TF coil set (tonne)	618.4
TF-coil current per coil,(MA)	2.4
TF coil current density (MA/m^2)	27.31
TF coil resistive power consumption [MW(e)]	331.4
Engineering summary	
Thermal conversion efficiency (%)	45
CD/heater [FWCD*] power (MW)	41.448
Total useful thermal power (MW)	3710
Gross electrical output power [MW(e)]	1669
Net electrical output power [MW(e)]	1092
14.06-MeV neutron load (MW/m^2)	7.991
Average LiPb blanket energy multiplication	1.4
First wall heat flux (MW/m^2)	1.936
Divertor max. heat flux (MW/m^2)	8.9

*Fast wave current drive

231-97

GENERAL ATOMICS

CENTRAL COLUMN (CC) AND TF COIL DESIGN

Inputs

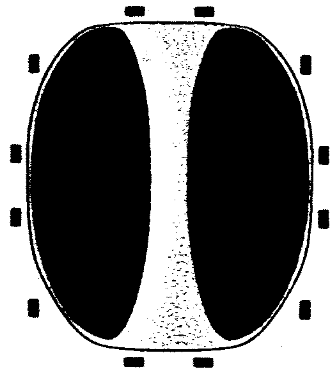
- Water–cooled
- Cu–alloy GlidCop-25
- Tapered ratio = 2.5
- Water-T_{in} at 30°C
- Water fraction = 15%
- T_{Cu}, coolant-T_{out}, Γ_n by iteration
- Current density (J_c)
- CC resistance (geometry, fluence, T_{Cu})
- H_2O pressure at 1 MPa

Design Criteria

- $V_{water} < 10$ m/s
- $T_{max\text{–}Cu} < 500$°C
- No inboard shield
- Γ_n-ave ≤ 8 MW/m^2
- Class–C waste

Design

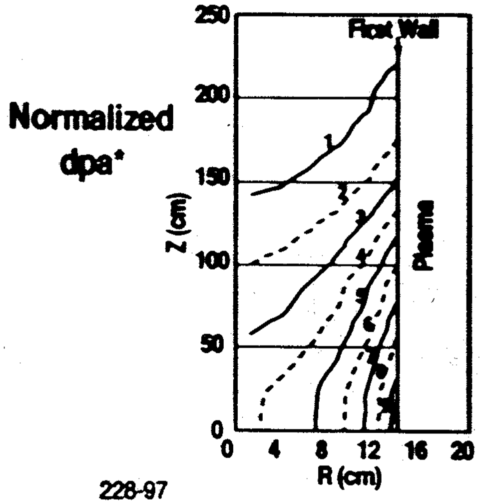
- Tapered central column
- Cylindrical outer leg and vacuum vessel



Results (R_o = 2.31 m)

- Water T_{out} = 52°C
- V_{max} = 9.7 m/s
- Water pumping power = 2 MW
- Resistive power = 331 MW(e)
- T_{max}-Cu = 71°C
- To meet Class-C waste criteria Al_2O_3 in GlidCop will have to be replaced† (e.g. SiO_2 or Y_2O_3)

†Fetter's evaluation and ARIES results



*TSI Research

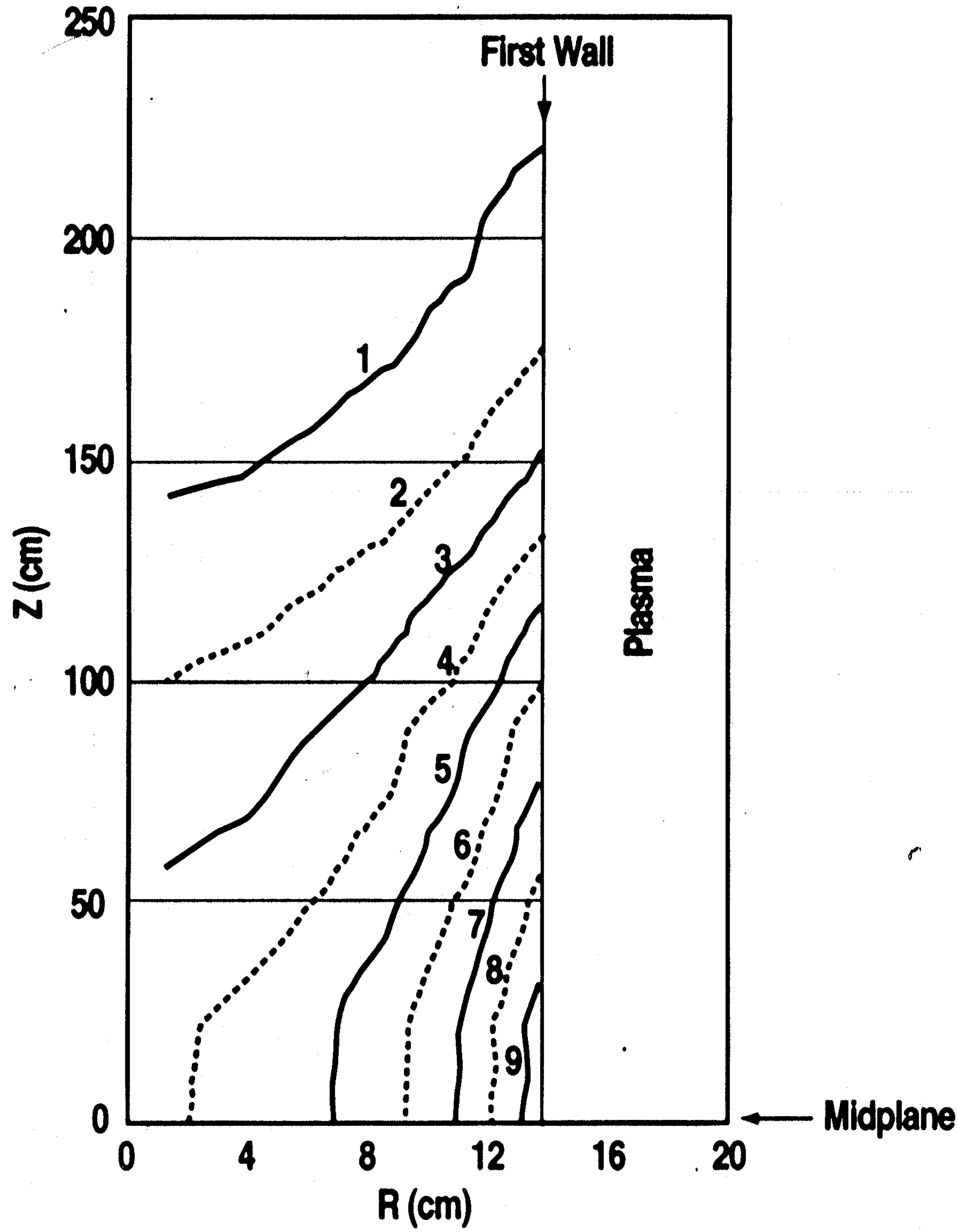
$$\text{CC Resistance} = 2\int_0^h \frac{1}{\displaystyle\int_0^R \frac{2\pi R\,(r,z)}{\eta(T,\text{dpa})}\,dr}\,dz$$

228-97

GENERAL ATOMICS

ATOMIC DISPLACEMENT IN COPPER*
(dpa PER MW•YR /m^2)

- Distribution of atomic displacement rate in the central column



*TSI research, SBIR phase – I report 1996

171-97/rs

GENERAL ATOMICS

IMPURITY CORE RADIATION
(TO TRADE OFF FW AND DIVERTOR HEAT FLUX)

Inputs

- n_e, He concentrations
- Other physics parameters
- Uniform impurity density
- Line radiation at coronal equilibrium
- Divertor flux expansion = 10
- Inclined divertor plate, radiation, geometry etc.

Design Criteria

- $\phi_{max\ divertor} < 10\ MW/m^2$
- $\phi_{ave\ FW} < 2\ MW/m^2$
- Favorable energy balance
- Rad. Temp Stability

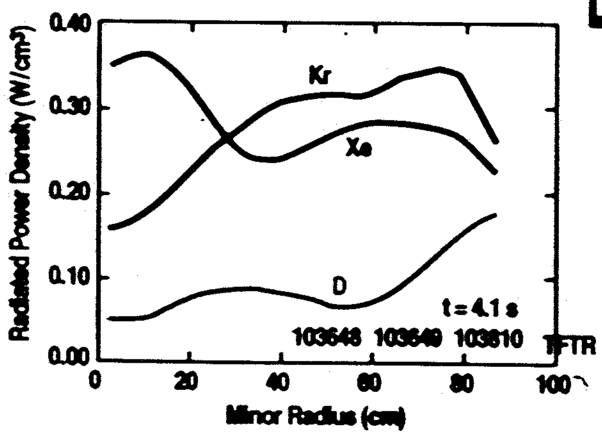
Design

- Uniform distribution $n_{Kr} = 0.0012\ n_e$ or $n_{Xe} = 0.0006\ n_e$
- Proton defect $\frac{n_D + n_T}{n_e} = 0.6$

$$n_i T_i = \frac{\beta_T B_T^2}{2\mu_o} (1 + Sn + S_T) \left[\frac{1 + f_z}{1 - f_z Z_z} + 1\right]^{-1}$$

Results (R_o = 2.31 m. Kr)

- $\phi_{FW} = 1.94\ MW/m^2$
- $\phi_{DW} = 8.9\ MW/m^2$
- $Z_{eff} = 2.87$
- $P_{Kr} = 477\ MW$
- $P_{Brem} = 26\ MW$



228-97

GENERAL ATOMICS

OBSERVATIONS

- Kr and Xe could be effective core radiation impurities
- ϕ_{div} could be adjusted and made equal to ϕ_{fw}
- TFTR showed supportive results
- Core radiation approach applicable to tokamak and LAR concept
- Effects on transport and confinement not clear
- Temperature instability can be a concern
- Concept and analysis verification experiment can be performed in present tokamak

FIRST-WALL BLANKET DESIGN (R_0 = 2.3 m)

"Applicable to any high power density fusion system"

Inputs

- Γ_n – Ave/max = 7.99/11.2 MW/m^2
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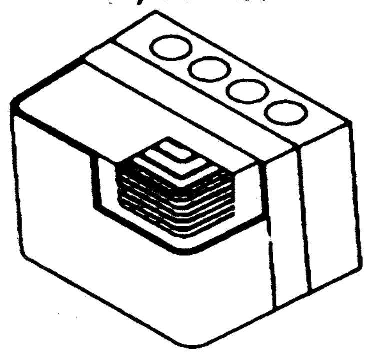
(A nest shell poloidal module)

- He–cooled, V-alloy, LiPb breeder*
- First wall, blanket



Results

- Design Criteria met.

Tube	Diameter	Wall Thickness
FW, mm	8	2
Blanket, mm	10	1.5

- Layer by layer volume fractions generated for neutronics iteration (Average volume fractions –V-alloy 15%, LiPb – 65%)
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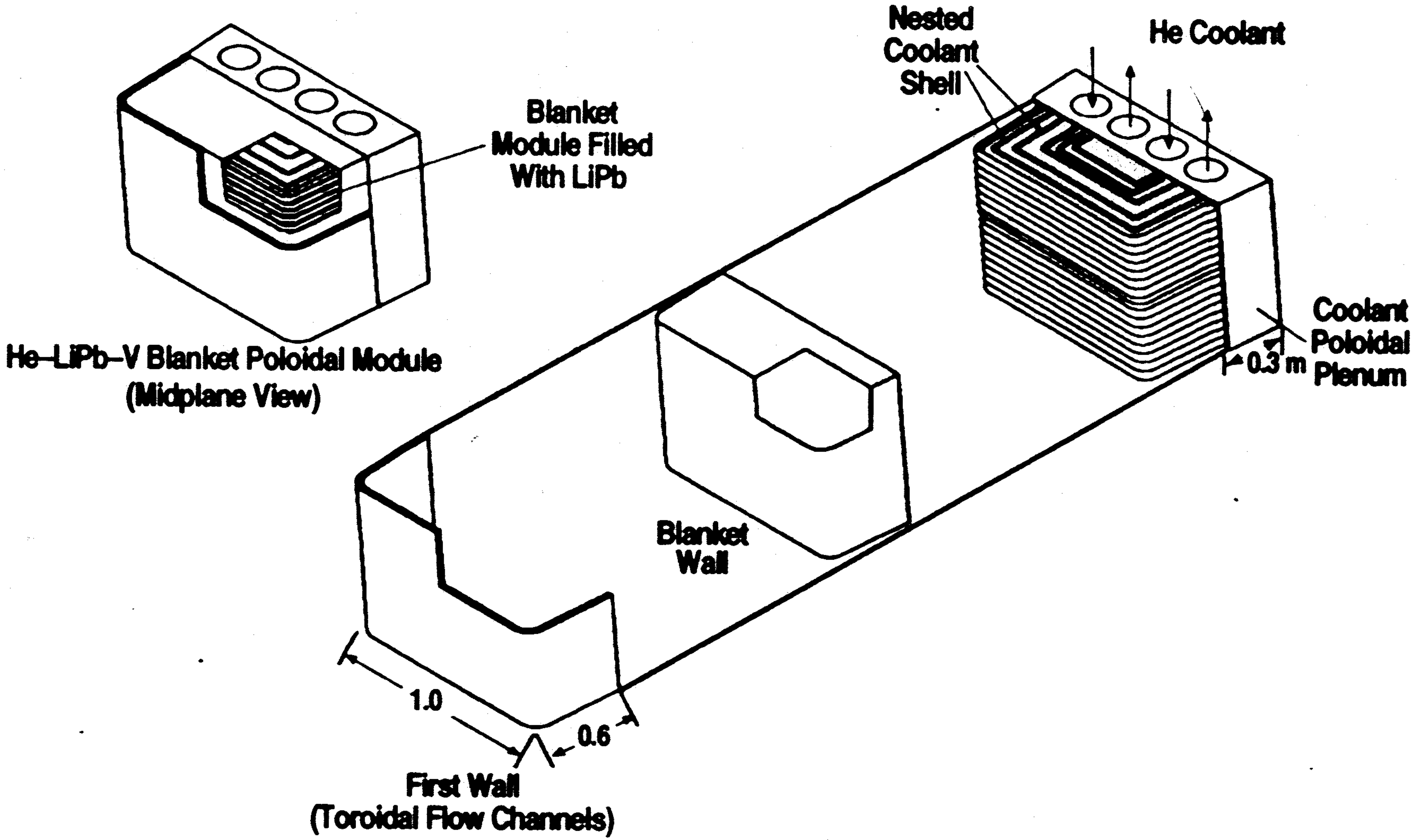
* Compatibility issue of He-impurites (O_2, H_2) with V-alloy not addressed


Blanket
Module Filled
With LiPb
He–LiPb–V Blanket Poloidal Module
(Midplane View)
Nested
Coolant
Shell
He Coolant
Coolant
Poloidal
Plenum
0.3 m
Blanket
Wall
1.0
0.6
First Wall
(Toroidal Flow Channels)

COST OF ELECTRICITY (COE)

Inputs

- Designs with different R_o
- Key materials unit cost:
  - \$300/kg — V-alloy
  - \$65/kg — Cu-alloy
- ARIES-RS system COE approach
- 30 FPY (availability 75%)
- Cu and V-alloys fluence life 15 MW yr/m^2

Costs Include

- Direct
- Indirect
- Over-night
- Levelized replacement cost for central columns and FW/blanket

Model

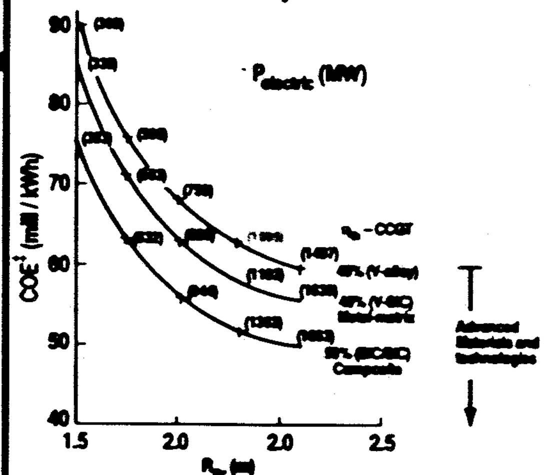
ARIES-RS costing code*

Plant components costs:

- Ratio to $P_{Thermal}$ or,
- Ratio to Pe-gross

Results (R_o = 2.31 m)

- Pe–net = 1092 MW
- Q = 2.9
- Total capital cost = \$3.45 B
- COE = 63.5 mill/kWh†
- CC replace 14 times
- OB-blanket replace 17 times

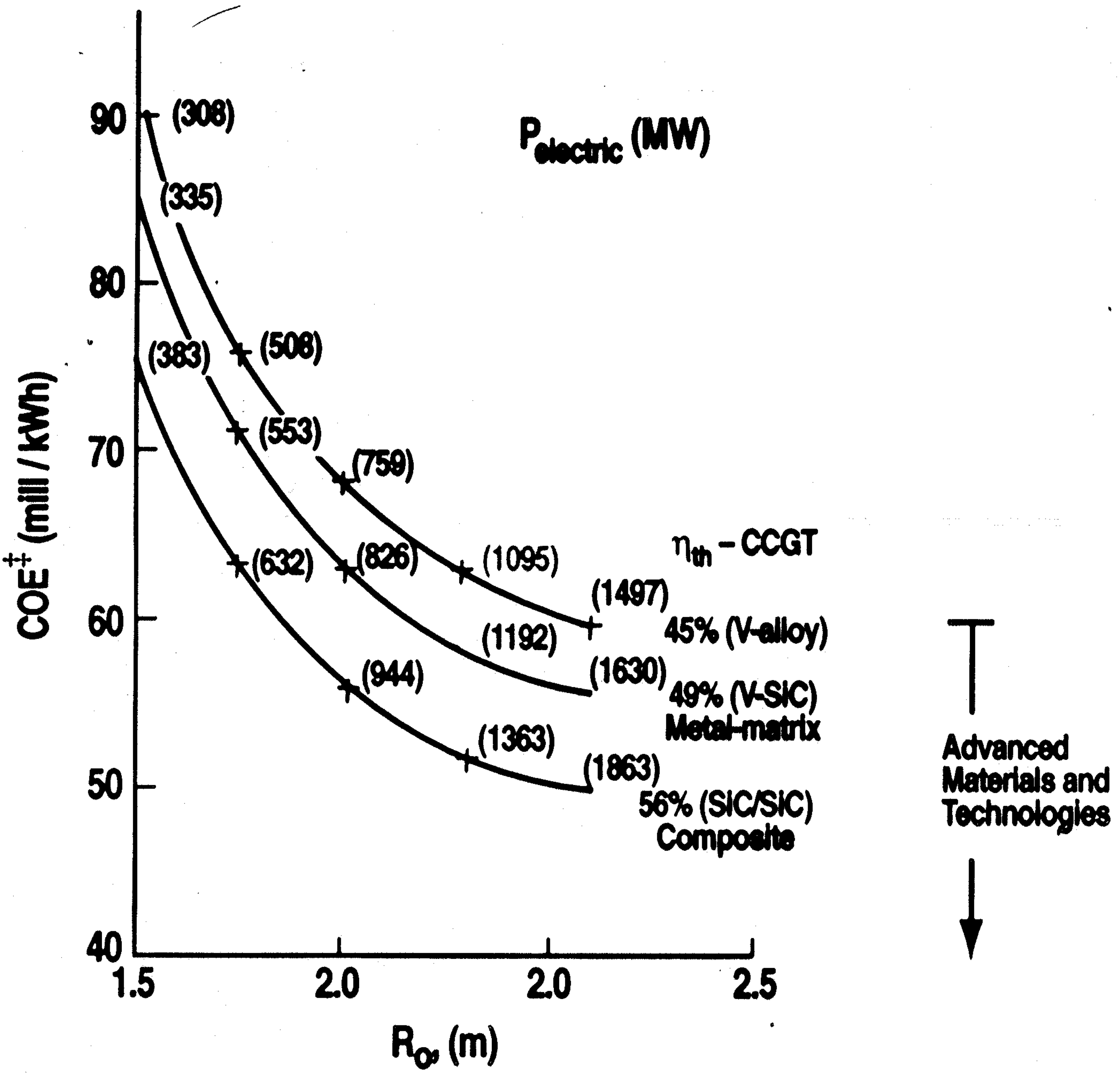


‡Including replacements

*Developed by C. Bathke (LANL) and R. Miller (UCSD)

†Coal and APWR: 50–60 mill/kwh beyond the year 2000

GA–LAR COE VERSUS PLANT SIZE AND TECHNOLOGY IMPROVEMENT



‡ Including replacements

SUMMARY OF ECONOMIC PARAMETERS

Account #	Account Title	$M (1992)
20.	Land and land rights	10.438
21.	Structures and site facilities	354.598
22.	Reactor plant equipment	789.106
22.1.1.	FW/blanket/reflector	52.118
22.1.2.	Shield	19.777
22.1.3.	Magnets	44.216
22.1.4.	Supplemental-heating/CD systems	76.196
22.1.5.	Primary structure and support	75.743
22.1.6.	Reactor vacuum systems	49.46
22.1.7.	Power supply, switching and energy storage	84.611
22.1.8.	Impurity control	16.658
22.1.9.	Direct energy conversion system	0.000
22.1.10	ECRH breakdown system	4.334
22.1.11	Reactor equipment	423.113
22.2.	Main heat transfer and transport systems	365.993
23.	Turbine plant equipment	403.092
24.	Electric plant equipment	101.385
25.	Miscellaneous plant equipment	55.837
26.	Special materials	38.254
90.	Direct cost (not including contingency)	1916
91.	Construction services and equipment	229.98
92.	Home office engineering and services	95.825
93.	Field office engineering and services	114.99
94.	Owner's cost	353.594
96.	Project contingency	471.459
97.	Interest during construction (IDC)	525.724
99.	Total cost ($$10^6$)	3708

Key design parameters:

Thermal power (MWth)	3710
Gross electric power [MW(e)]	1669
Unit overnight cost [$/kW(e)]	3182
Net electric power [MW(e)]	1092
Engineering Q-value, QE	2.908
Capital return [mill/kW(e)h]	49.495
Plant availability	0.75
O&M (1.68%) [mill/kW(e)h]	9.16
W/B/R replace.[mill/kW(e)h]	4.047
Decommissioning [mill/kW(e)h]	0.5
Fuel [mill/kW(e)h]	0.03
LSA*=2 total COE [mill/kW(e)h]	63.5 at η_{th}= 45% 59.1 at η_{th}= 49% 53.0 at η_{th}= 56%

*Level of safety assurance

231-97

GENERAL ATOMICS

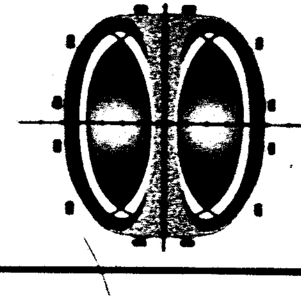
DEVELOPMENT PATH/GOALS CAN BE DEFINED FOR THE LAR CONCEPT (DEPENDING ON THE SUCCESSFUL DEVELOPMENT OF THE FOLLOWING)

- Physics: β_t ~ 60%, BS-fraction ~ 90%, high CD efficiency, startup and disruption control

- Core impurities radiation: Further verification and possible use for heat flux distribution and shutdown control

- Technology
  - First wall/blanket, peak/ave Γ_n ~ 12/8 MW/m^2
  - Central column J_c for burn control
  - Unshield central column and brittle material design
  - He/V system at 15 MPa and T_{out} at 650°C
  - Compatibility of He-impurities (O_2, H_2) with V-alloy
  - 15 MPa CCGT system with η_{th} ~ 45%
  - Low activation V and Cu alloys
  - Advanced materials for higher performance (V/SiC metal matrix — η_{Th} ~ 49%, SiC/SiC ceramic composite — η_{Th} ~ 56%)

A POSSIBLE LIGHT FOR OUR FUSION JOURNEY



- **Aggressive LAR physics and technology approaches could lead to an economically competitive fusion power system**

- **Core impurity radiation could become a powerful control knob**

- **Low activation(environmentally benign) design is possible**

- **Physics and technology have to be developed in concert, minimum COE is limited by technology**

- **The possibility of an attractive endpoint power system contributes to the motivation for following the ST development path**