Documentation of System Cost Accounts and Algorithms

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ARIES Project Meeting at UW-Madison

Cost Account Status

Documented ARIES Cost Accounts are shown below:

- ✓ **Accounts 20, Land and Land Rights** — **Previously Reported**
- ✓ **Accounts 21, Structures and Site Facilities** — **Previously Reported**
- **Partially Acct 22, Power Core Plant Equipment**
  - ✓**Acct 22.01, Fusion Energy Capture and Conversion (FWB, shielding) Previously Reported**
  - **Acct 22.02, Plasma Confinement (Being developed by Dragojlovic/Bromberg/Kessel)**
  - **Acct 22.03, Plasma Formation and Sustainment** — **Reported This Meeting**
  - **Acct 22.04, Vacuum, Power Core** — **Reported This Meeting**
  - **Acct 22.05 Primary Structure and Support, Power Core** — **Reported This Meeting**
  - **Acct 22.06 – 13 Power Supplies, Main HT&T, Cryo, Rad Matls, Fuel Handl, Maint, I&C, and Other Plant Equipment** (yet to be done)
- **Account 23 Turbine Plant Equipment** — **To Be Done**
- **Account 24 Electric Plant Equipment** — **To Be Done**
- **Account 25 Heat Rejection Equipment** — **To Be Done**
- **Account 26 Misc Plant Equipment** — **To Be done**
- **Account 27 Special Materials** — **To Be Done**
- **Accounts 91, 92, 93, 94, 95, 96, 97, 98** — **Reported This Meeting**

Cost Account Numbering Changes

A few changes in the Cost Accounts are made to better agree with ASC & Gen IV/and GA MHR

- 22 Power Core Plant Equipment Þ Power Core Equipment
- 23 Turbine Plant Equipment Þ Turbine - Generator Equipment
- 24 Electrical Plant Equipment Þ Electrical Equipment
- 23.03 Heat Rejection System Þ 25 Heat Rejection Equipment ASC currently has this as Account 26
- 23.03.01 Þ 25.01 Water Intake Common Facilities
- 23.03.02 Þ 25.02 Circulating Water Systems
- 23.03.03 Þ 25.03 Cooling Towers
- 23.03.04 Þ 25.04 Other Heat Rejection Systems
- 25 Miscellaneous Plant Equipment Þ 26 Miscellaneous Equipment
- 26 Special Materials Þ 27 Special Materials

Costing Groundrules

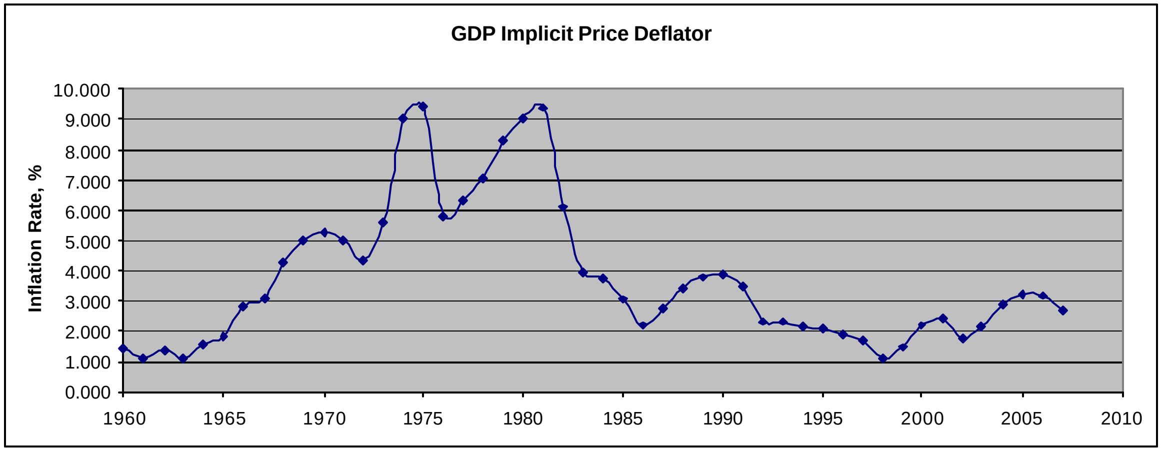
- **Inflation changes are measured with US Commerce Department Gross Domestic Product Implicit Price Deflator**
- **I have a spreadsheet that contains all annual and quarterly data back to 1929 that will convert any year dollars to any other year dollars**

Conversion Calculator

Ref Year	Final Year	
2005.0	2008.0	Conv Factor
113.001	123.254	1.09074

Common Conversions

Ref Year	Final Year	Factor
1980	1992	1.5985
1980	2008	2.2807
1992	2008	1.4268
1999	2002	1.0646
2000	2008	1.2325
2002	2008	1.1830



Utilization of LSA Factors

Generomak and ESECOM (Senior Committee on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy) report developed a Level of Safety Assurance (LSA) methodology that would allow comparison plants with differing degrees of inherent safety and hazards with respect to radioactive materials. They created 4 levels of LSA, listed below.

LSA = 4 Denotes active protection (i.e., active engineered safety systems are required); the system does not meet minimum requirements for inherent safety.

LSA = 3 Safety is assured by passive mechanisms of release limitation as long as severe violations of small-scale geometry are avoided (e.g., large coolant pipe breaks).

LSA = 2 Safety is assured by passive mechanisms as long as severe reconfiguration of large-scale geometry is avoided.

LSA = 1 Safety is assured by passive mechanisms of release limitation for any accident sequence; radioactive inventories and material properties preclude fatal release regardless of power plant's condition.

Utilization of LSA Factors

LSA assessment of prior ARIES reactors (ref: ARIES-II-IV Systems Studies for ARIES-I' to ARIES-IV)

- ARIES-1 (revisited) (LSA 2)
- ARIES-I' LSA 1
- ARIES-II LSA 2
- ARIES-III LSA 2
- ARIES-III' LSA 2
- ARIES-IV LSA 1
- ARIES-RS LSA 2
- ARIES-AT LSA 1

Greatest LSA savings are in the areas of Power Core Building, other structures, Heat Transfer and Transport w/ IHX or He w/ Double-Walled Steam Generator

Table 1-1. ARIES LSA Factors for Plant Direct Cost Accounts

Acct.	Account Title	LSA=4	LSA=3	LSA=2	LSA=1
20	Land and Land Rights	1.00	1.00	1.00	1.00
21	Structures & Site Facilities				
	Power Core & Hot Cell Buildings	0.60	0.90	0.96	1.00
	Turbine –Generator Building	1.00	1.00	1.00	1.00
	Other Structures & Improvements	0.60	0.67	0.67	1.00
22	Power Core Equipment				
	Fusion Energy Capture & Conversion	0.90	0.95	1.00	1.00
	Plasma Confinement (TF, PF, CF)	0.90	0.95	1.00	1.00
	Heat Transfer & Transport w/IHX or He with Double Walled SG	0.60	1.00	1.00	1.00
Or,	Heat Transfer & Trnspt, Other options	0.90	1.00	1.00	1.00
	All Other Reactor Plant Equipment	0.85	0.94	0.94	1.00
23	Turbine Plant Equipment	1.00	1.00	1.00	1.00
24	Electrical Plant Equipment	0.75	0.84	0.84	1.00
25	Heat Rejection Plant Equipment	1.00	1.00	1.00	1.00
26	Miscellaneous Plant Equipment	0.85	0.90	0.93	1.00
	All Other Direct Cost Accounts	1.00	1.00	1.00	1.00

Utilization of LSA Factors

Table X-2. ARIES-AT Indirect Cost Factors for LSA Ratings (% of Direct Costs)

Highlighted accounts reflect potential LSA savings

	LSA = 4		LSA = 3		LSA = 2		LSA =1	
Account	Factors[a]		Factors[a]		Factors[a]		Factors[a]	
90 Direct Costs	1.00000		1.00000		1.00000		1.00000	
91 Con Serv & Eq	0.15100		0.12800		0.12000		0.11300	
92 Home Office Engr	0.05200		0.05200		0.05200		0.05200	
93 Field Office Engr	0.08700		0.06400		0.06000		0.05200	
Subtotal (ID costs)	**0.29000**		**0.24400**		**0.23200**		**0.21700**	
94 Owner's Cost (% D+ID ; % D)	0.1500	0.1935	0.1500	0.1866	0.1500	0.1848	0.1500	0.1826
Total Indirect Costs	**0.48350**		**0.43060**		**0.41680**		**0.39960**	
Total Dir + Indir costs	**1.48350**		**1.43060**		**1.41680**		**1.39960**	
95 Process Contingency	0		0		0		0	
96 Project Contingency (% D+ID ; % D)	0.1893	0.2808	0.1793	0.2565	0.1688	0.2391	0.1465	0.2050
97 Interest During Cnstr (% D+ID ; % D)	0.1652	0.29146	0.1652	0.27871	0.1652	0.27355	0.1652	0.26508
Total Overnight Costs	**2.05576**		**1.96581**		**1.92945**		**1.86968**	

[a] Factors are a ratio of indirect cost item to direct cost (90) unless noted (94, 96, 97)

ASC code currently calculates Accounts 94, 96 and 97 as a function of direct costs only, whereas they are defined to be functions of both direct and prior indirect costs. The latter will reflect changes in indirects also.

Primary Basis for Costing Algorithms

- Schulte, et. al. "Fusion Reactor Design Studies – Standard Accounts for Cost Estimates", Pacific Northwest Laboratory, PNL-2648, May 1978 defined all the fusion power plant cost accounts and prescribed the definition of the indirect cost accounts and some recommended algorithms
- Starlight Conceptual Reactor study (Waganer) (1980) had a very complete and detailed cost assessment that is well documented, but now largely out of date
- The Generomak report (Delene, Sheffield) (1986) developed a basis for a parametric reactor design with modeling algorithms based largely on Starfire and a few other designs. This was the first use of LSA factors. Some indirect costs were modified and defined in more detail.
- ARIES studies (Bathke, Miller) adopted the Starfire and the Generomak cost basis and modeling in the ASC code
- ITER and FIRE (Snowmass Cost Assessment, 2002, Waganer) provide some current more detailed system cost estimates. The ARIES-AT vacuum vessel detailed study provides more in-depth costing estimates.
- "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems", The Economic Modeling Working Group of the Generation IV International Forum, GIF/EMWG/2007/004, Revision 3, September 26, 2007 provides a basis for collaborative assessment between advanced fission and fusion power plants

General Recommendations

Spare Parts

- **The Starfire report provides a overall spare parts allowance at the 21 through 25 account level, specifically 2% for Accounts 21, 22, and 23, 4% for Account 24 and 3% for Account 25.**
- **ARIES has not specifically addressed spares**
- **Recommend spares are included in the individual direct cost accounts and algorithms**

Contingency

- **Contingency in Starfire was at the major direct cost account level.**
- **But later studies, including ARIES, included contingency as an indirect cost Account 96, Project Contingency. Account 95, Process Contingency is typically zero as the process contingency should be zero for a mature design.**
- **Gen IV has a separate account, 29, for direct cost contingency. Gen IV also has contingencies on indirect costs**

Contingency will be discussed later in much more detail

Summary of Direct Cost Accounts

Account 22.01 Fusion Energy Capture and Conversion

This account contains the core systems needed for the capture, conversion, and containment of the fusion reaction products.

22.01.01	First Wall and Blanket, replaceable, inboard and outboard
22.01.02	Second Blanket, life of plant,outboard (maybe inboard)
22.01.03	Divertor Assembly, upper and lower, replaceable
22.01.04	High Temperature Shielding, outside of blanket and divertor, life of plant
22.01.05	Low Temperature Shielding, outside of high temperature shield, life of plant
22.01.06	Penetration Shielding (low temperature, active and passive)

The typical cost estimating approach for the conceptual design studies is to develop representative installed component costs based on a unit cost basis, in this case, dollars per kg. A table of candidate materials and costs has been provided to suit the design requirements. Costs are developed for a range of component and subsystem complexity and manufacturing approach. Using the unit cost approach allows scalability to smaller/larger/thinner/thicker component sizes. Specific radial builds will be used to define composition of the components.

In the case of replaceable components, the initial set of components will be included in the initial capital costs. Replacement costs will be in the O&M costs.

Summary of Direct Cost Accounts

Account 22.02 Plasma Confinement

This account contains all the magnetic coils that confine and control the plasma. These coils create the toroidal and poloidal fields necessary to contain the plasma. These coils are typically superconducting coils. The superconducting coils can be low temperature (~4K) or superconducting coils in the range of 70K. In addition, there is a set fast-acting control coils to provide the necessary plasma stability.

		Cost Account Mgr
22.02.01	Toroidal Field Coils	Bromberg
22.02.02	Poloidal Field Coils (Central Solenoid and Outer Poloidal	Bromberg
22.02.03	Feedback Control Coils (Normal conducting)	Kessel

To date, each set of normal or superconducting coils have been designed and built specifically for a single application. Hence any design or fabrication learning and quantity purchase is not applicable to the next device. However, the superconducting cable design and fabrication has made significant progress, especially in the higher temperature superconductors and fabrication. New algorithms are being formulated to incorporate the current knowledge base and extend it to future fusion power plant coil systems.

Summary of Direct Cost Accounts

Account 22.03 Plasma Formation and Sustainment

The components in this subsystem account is associated with the initial formation of the plasma and the continued sustainment of the proper plasma condition for the steady-state productive output of the plasma. These subsystems are subdivided into various types of radio frequency (RF) or neutral beam (NB) energy injected into the plasma to heat or properly condition the plasma to achieve the necessary current drive.

22.03.01	Heating and Current Drive (Primarily Steady State)
22.03.02	Startup
22.03.03	Stability Control (Primarily Transient)
22.03.04	Plasma Fueling and Constituent Control

The next few slides describe the Plasma Formation and Sustainment Subaccounts

Summary of Direct Cost Accounts

Account 22.03.01 Heating and Current Drive

This subsystem or a combination of subsystems provides continuous heating and current drive for the plasma to sustain the nominal plasma condition for proper operation. This subsystem nominally operates in steady state-condition, but it may assist the startup systems for initial heating and current drive.

Candidate subsystems options

22.03.01.01 Ion Cyclotron Resonance Frequency (ICRF) Fast Wave Heating and Current Drive
22.03.01.02 Lower Hybrid (LH) Wave Plasma Heating and Current Drive
22.03.01.03 Electron Cyclotron Resonance Frequency (ECRF) Plasma Heating and Current Drive
22.03.01.04 Neutral Particle Beam Plasma Heating, Current Drive and Rotation

Starfire used Lower Hybrid for heating and current drive. They used 432 cross field amplifiers at 1.677 GHz at 420 kW each to deliver 90 MW heating power to the plasma. In present 2008$, the 432 CFAs would cost $27.10M, the grills and other delivery hardware would cost $49.29M, and initial CFA spares and grills would cost $12.29M for a total present cost of $88.68M.

Summary of Direct Cost Accounts

Account 22.03.01 Heating and Current Drive (continued)

ARIES-I, -II, -IV, -RS, and –AT chose to use a combination of Lower Hybrid and/or ICRF heating and current drive. Generally, the reported costs were not separable so no detailed comparison could be made. The ARIES-II-IV Systems Studies did document the unit costs as shown below. It is presumed these unit costs included the RF generators as well as the delivery systems, but not the power supplies

Source	Type, Frequency	Del Pwr, MW	Rptd Cost, 92M$	LSA4 Cost, 92M$	$/W , 1992$	$/W, 2008$
ARIES Sys Studies	NBI, 2 MeV	NA			$3.45	$4.92
ARIES Sys Studies	LH, 80 MHz?	NA			$1.49	$2.13
ARIES Sys Studies	ICRF, 80 MHz	NA			$1.15	$1.64
ARIES Sys Studies	ICRF, 158 MHz	NA			$1.15	$1.64
ARIES Sys Studies	ICRF, 250 MHz	NA			$2.30	$3.28
ARIES Sys Studies	ICRF, 800 MHz	NA			$2.30	$3.28
ARIES Sys Studies	ICRF, 2500 MHz	NA			$2.30	$3.28
ARIES Sys Studies	ICRF, 8000 MHz	NA			$2.30	$3.28
Starfire	LH, 1.667 GHz	90		$88.680	$0.99	$1.41
ARIES-I (LSA=2)	ICRF/LH	96.707	$118.592	$126.162	$1.30	$1.86
ARIES-I' (LSA=1)	ICRF (/LH?)	202.5	$236.5	$278.235	$1.37	$1.96
ARIES-II (LSA=2)	ICRF/LH	66.1	$194.3	$206.702	$3.13	$4.46
ARIES-III (LSA=2)	NBI	172	$528.8(90$)			
ARIES-III (LSA=2)	NBI	172	$559.9	$595.606	$3.46	$4.94
ARIES-III' (LSA=2)	NBI	163.2	$529.2	$562.979	$3.45	$4.92
ARIES-IV (LSA=1)	ICRF/LH	68.0	$175.7	$206.706	$3.04	$4.34
ARIES-RS (LSA=2)	ICRF/HFFW/LH	80.773	$164.211	$174.693	$2.16	$3.09
ARIES-AT (LSA=1)	ICRF/LH	37.441	$37.060	$43.600	$1.16	$1.66
US ITER Team	ICRF	Not specified	First of a kind including R&D, salaries, and contingency			$5-6

Reported values do not match provided algorithms

Summary of Direct Cost Accounts

Account 22.03.02 Startup

These subsystems are dedicated to bringing the plasma from no plasma conditions up to the plasma conditions for full power, steady-state operation. This subsystem also may be used when transitioning from a partial power condition up to a higher level of power output.

Starfire employed its steady-state LH subsystem as its plasma startup subsystem. ARIES-I used ICRF for plasma heating and ECRH as plasma breakdown. All other ARIES designs (including ARIES-I') used ECRH as the plasma breakdown subsystem. ARIES did not technically document their startup subsystems, however they did include the ECRH plasma breakdown subsystems in their cost estimate.

Table X-6 ECRF Plasma Breakdown Subsystem Costs from ARIES Studies[10, 23]

ECRF	Del Power, MW	1992$,LSA 1, 2	1992$, LSA4	2008$, LSA4	Unit Cost, $/W
ARIES Sys Studies, A-1 to A-RS					$2.60 (Constant)
ARIES Sys Studies, A-AT					$2.78 (Constant)
ARIES-I' (LSA=2)	Data Not Found	$3.900	$4.149	$5.920	TBD
ARIES-II (LSA=2)	Data Not Found	$4.300	$4.574	$6.527	TBD
ARIES-III' (LSA=1)	Data Not Found	$4.300	$5.059	$7.218	TBD
ARIES-IV (LSA=2)	Data Not Found	$3.900	$4.149	$5.920	TBD
ARIES-RS (LSA=2)	Data Not Found	$4.334	$4.610	$6.578	TBD
ARIES-AT (LSA=1)	Data Not Found	$3.975	$4.677	$6.673	TBD

Reported values do not match provided unit costs
Constant costs do not provide flexibility in power levels

Summary of Direct Cost Accounts

Account 22.03.03 Stability Control

This subsystem is to ensure the stability of the steady-state plasma and is primarily a transient operation, with fast acting, high power feedback to the subsystems to actively control the plasma conditions. The candidate subsystems are Electron Cyclotron Resonance Frequency (ECRF) and Neutron Particle Beams.

This is a new function added to the Plasma Formation and Sustainment account and it needs further investigation and definition. Due to the fast acting and high power consumption, the unit costs may be higher per unit of delivered power. It is presumed these are dedicated subsystems and will not use the primary heating and current drive subsystems.

Summary of Direct Cost Accounts

Account 22.03.04 Plasma Fueling and Constituent Control,

previously included in Account 22.5, Fuel Handling and Storage

These are the subsystems that provide the fueling, both steady-state as well as transient, to maintain the desired plasma fuel mixture. In addition to providing the nominal mix of deutritium and tritium, there may need to be some adjustment of the D-T mixture to fine tune the fuel mix in the plasma. There also may be some need to inject some other elements to adjust the radiation characteristics of the plasma. These systems or a dedicated variation of these systems may also be used to inject "killer" pellets to rapidly quench the plasma, if necessary.

22.03.04.01 Pellet Injection Fueling and Constituent Control

Generally, the ARIES studies technically defined the pellet injection subsystems. The ARIES-II-IV Systems Studies provided a cost algorithm for the pellet injector as $6.07 M (LSA = 4, 1992$) each with 2 injectors required. This algorithm was applied from ARIES-1 to ARIES-RS. For ARIES-AT, Ron Miller updated the leading constant to $6.48 (LSA = 4, 1992$). Since the cost data were never published, these data is not confirmed.

22.03.04.02 Neutral (Particle) Beam Injection (NBI) Fueling and Constituent Control –

If neutral beams are used in the current drive subsystem, altering the fuel mix in the particle beam may be a convenient and low or no cost way to fuel the plasma.

Summary of Direct Cost Accounts

Account 22.04 Vacuum, Power Core

This account provides all the equipment and plumbing necessary to provide a high quality vacuum for the power core. Included are refrigerators, cryogenic and roughing pumps, vacuum ducts and cryogenic pumps. It does not include the vacuum vessel as it is considered as a structural item, see Account 22.05.03. Nor does it include the shielding of the vacuum ducts as that will be included in the power core shielding, Account 22.01.05, Low Temperature Shielding.

Vacuum systems for other subsystems, such as radiation materials treatment are included in those subsystems. It is TBD if vacuum leak detection subsystem is included in this account or in instrumentation.

The Starfire report has the best documentation of the vacuum equipment subsystem, costing around $25M in 2008$ plus the cost of the vacuum pumping ducts, which are dependent on their presently uncalculated mass.

22.04.01	Helium Liquefier-Refrigerators
22.04.02	Cryogenic Vacuum Pumps
22.04.03	Roughing or Backing Pumps
22.04.04	Vacuum Pumping Ducts *(vac duct shielding in 22.01.06)*
22.04.05	Plumbing, Cryogenic
	Leak Detection? Or include in Instrumentation?

Summary of Direct Cost Accounts

Account 22.04 Vacuum, Power Core (Continued)

ARIES II-IV adopted or created the algorithm for the power core vacuum equipment cost

ARIES Designs	1992$	2008$
II-IV, SPPS, RS	$4.09 x mass flow rate	$5.84 x mass flow rate
AT	$4.37 x mass flow rate	$6.24 x mass flow rate

From the ARIES-AT full summary printout from the ARIES web site, the exhaust mass flow rate is not evident. The ARIES-AT vacuum pumping speed is reported as 174.697 m^3/s (174,697 liters/sec) for an unknown species of gas, probably total gas load pumping speed, not just helium. This compares to the Starfire data of 200 m^3/s total gas load or 125 m^3/s helium.

To obtain a rough estimate of the ARIES-AT vacuum subsystem equipment costs without knowing the mass flow rate, the cost of the vacuum vessel (the vacuum vessel portion ($52.50M in 2008$ for LSA = 4) can be subtracted from the total ARIES-AT LSA=4 vacuum subsystem costs of $165.80M for a vacuum equipment cost of $113.29M in 2008$ for an LSA=1 plant, which seems to be very high.

In the ASC code, it calculates unit costs for different elements of the vacuum vessel and if those are used, the Vacuum Vessel would be in the range of $125M and the Vacuum System cost would be approximately $40M.

Summary of Direct Cost Accounts

Account 22.04 Vacuum, Power Core (Continued)

ITER Technical Basis Report has a very detailed definition of their vacuum equipment subsystem that includes high vacuum pumping, roughing/backing, and diagnostic/ roughing subsystems. They have 10 cryopumps, either active or regenerating, during the long plasma pulses. Their anticipated steady-state helium pumping speed is 60 m^3/sec. The ITER vacuum pumping equipment total cost escalated to 2008$ is $44.00M, per the Snowmass cost analysis of ITER and FIRE. ITER estimated $151.1M (2008$) for the cryoplant, cryo lines, and cryo containers. So the comparable ITER cost would be $195.1M.

The FIRE Engineering Status Report of 2001 reported that it would use 16 cryopumps with an effective pumping speed of 32 m^3/sec for helium. This report noted that the lower burn fraction would increase an equivalent torus pumping requirement from prior Starfire and ARIES conceptual designs. The Snowmass cost analysis of FIRE vacuum equipment would be $19.33M in 2008$.

This subsystem needs some more clarity regarding pumping speeds and cryogenic requirements before any recommendations can be made. This subsystem should be related to the pumping speed needed, probably for helium, and the distance from the power core chamber and the cryogenic and roughing pumps. From Starfire data, it would seem the refrigeration and liquefaction is the major cost. Cryopumps and roughing pumps should be a reasonable cost. The weight and cost of the pumping ducts should be added.

Summary of Direct Cost Accounts

Account 22.05 Primary Structure and Support, Power Core

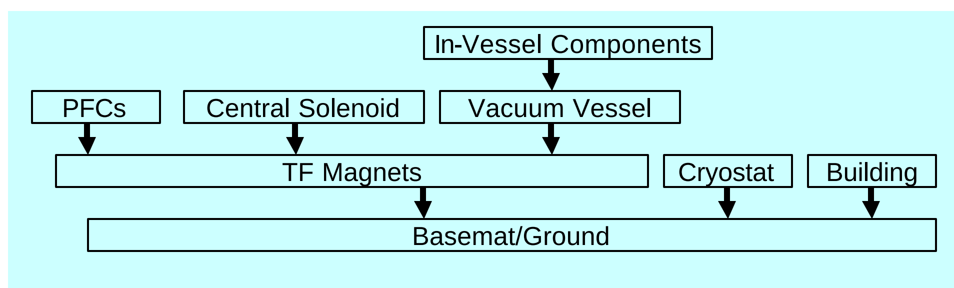
This account provides primary structure and support for the power core, which is very massive. Several of the main power core elements support each other. This subsystem transfers the gravity and seismic loads to the building structures.

22.05.01	Center Post, Power Core	22.05.06	Common Dewar
22.05.02	Bucking Cylinder	22.05.07	Anti-Torque Structure
22.05.03	Vacuum Vessel	22.05.08	Carry-Through Structure
22.05.04	Cryostat and Thermal Shield	22.05.09	Shield Pedestal
22.05.05	Thermal Isolation Struts	22.05.10	Equipment Support Structure

Starfire reported the technical definition, mass, material, unit cost, and the total cost of each primary structure element, per the account structure above.

Interestingly, ITER chose not to identify a cost account for primary structure and support, rather they incorporated the supports into the other primary machine and building accounts.

ITER Schematic of Support Hierarchy



Summary of Direct Cost Accounts

Account 22.05 Primary Structure and Support, Power Core (continued)

On the other hand, ARIES-AT has a single algorithm for the entire primary structure and support. Cost of Primary Structure = $0.20M x Volume ($m^3$) in 1992$ for LSA = 4.

The systems code summary listed a structural volume of 149.910 m^3 and a mass of the fusion power core structure of 899.459 tonnes. It is not clear if these data refer to the same structural element. If it is the same element, the effective density is 6000 kg/m^3. If the structure is made of steel with a theoretical density of 7800 kg/m^3, then the fractional density is 0.769. The structure material and fractional density is never reported.

Assuming that the ARIES-provided structural volume is correct for the total primary structure, the algorithm would yield a total cost of $29.982M (in 1992 for LSA = 4). This compares to a reported cost of $31.686M (in 1992 for LSA = 4).
However the basis still remains unclear.

Summary of Direct Cost Accounts

Account 22.05 Primary Structure and Support, Power Core (continued)

The Primary Structure and Support data for the ARIES-RS has exactly the same formulation with much higher volume and mass values for the structure. The structure algorithm is slightly lower at $0.184M x volume of the primary structure. With a structural volume of 271.132 m^3, this would yield an LSA = 4 cost estimate of $49.89M as compared to the reported value of $56.86M. This set of data cannot be confirmed either.

- **We must confirm what these data really refer to (structural volume, mass of FPC structure, and bucking cylinder mass.**
- **We must identify what element are really being considered and estimated.**
- **If we identify the bucking cylinder mass, how is it estimated?**
- **Do we need to add the cryostat volume to the structural volume algorithm?**
- **Since a bucking cylinder is identified in the AT summary, why does show up only a very few of the CAD drawings?**

The next few slides describe the Primary Structure, Power Core Subaccounts

Summary of Direct Cost Accounts

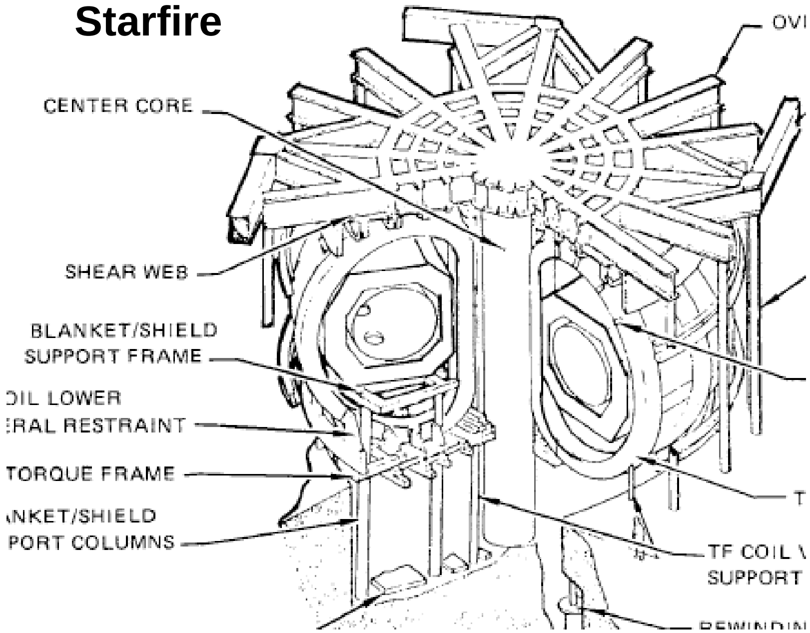
Account 22.05.01 Center Post, Power Core

The center post is the central support element that provides support to counteract the inward radial forces of the TF magnet coil sets. This element is used in the cases when the TF coils are not wedged on themselves, a technique which converts the radial forces into circumferential hoop forces. If the TF coils are truly wedged or if a bucking cylinder is used, a Center Post probably will not be required.

Starfire used a cryogenic center post made of G-10CR glass-cloth/epoxy laminate weighing 279 tonnes, which cost $20/kg (1980$) or $45.62/kg (2008$). It also served as the bucking cylinder and housed the EF/OH coils.

I do not believe any ARIES design used a center post, other than ARIES-ST, but instead chose to use hollow core bucking cylinder to counteract the inward TF magnetic forces. ARIES-ST had a completely different design that used a central conductor core for the TF coils and its cost was included in the TF coil cost.

Starfire



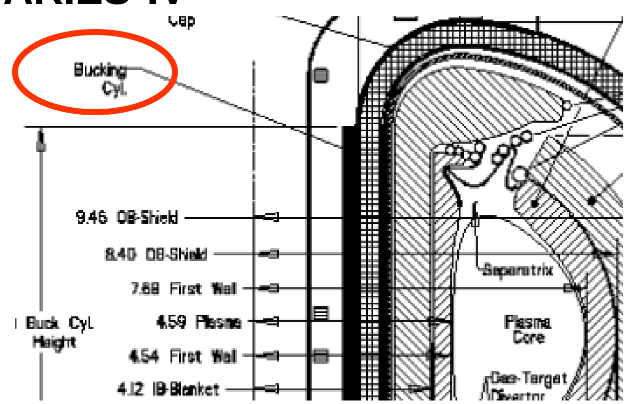
Summary of Direct Cost Accounts

Account 22.05.02 Bucking Cylinder

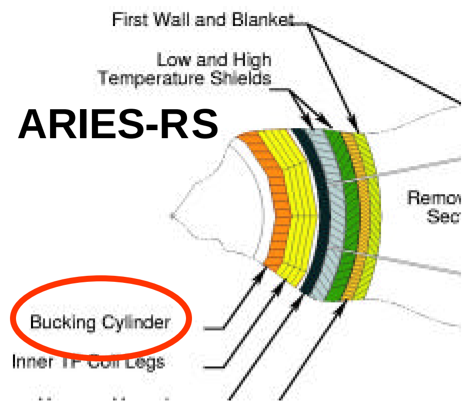
In most tokamak designs, a center post is not used. Instead, the center is hollow and uses a bucking cylinder to counteract the inward coil forces.

ITER uses this approach. Most ARIES designs used this bucking cylinder approach. ARIES Pulsar, IV, RS identified the use of a bucking cylinder and these bucking cylinders were shown in the CAD drawings and their masses reported in the systems code summaries. However, it is not evident that the cylinders are included in the structural volume, masses or costs.

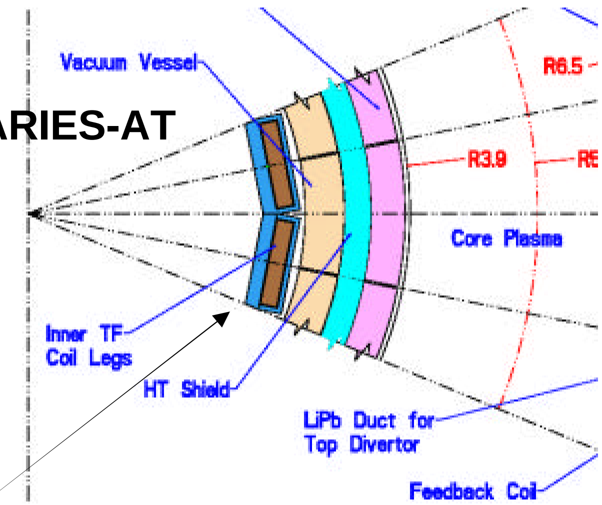
ARIES-IV



ARIES-RS



ARIES-AT



In the ARIES-AT CAD drawings, the bucking cylinder is not identified, but it is considered to be an integral part of the inner leg of the TF magnet structure. However, in the systems code summary report, ARIES-AT provided a separate bucking cylinder mass of 130.649 tonnes, but no volume is provided. It is not evident the mass or cost is included in either the structure or coil systems.

Summary of Direct Cost Accounts

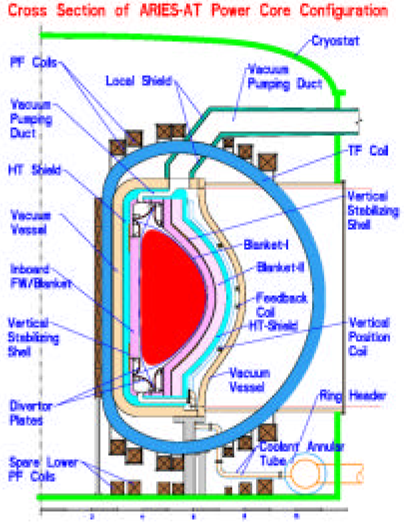
Account 22.05.03 Vacuum Vessel

The vacuum vessel is typically the next outboard subsystem from the shielding. This account includes structural elements only that:

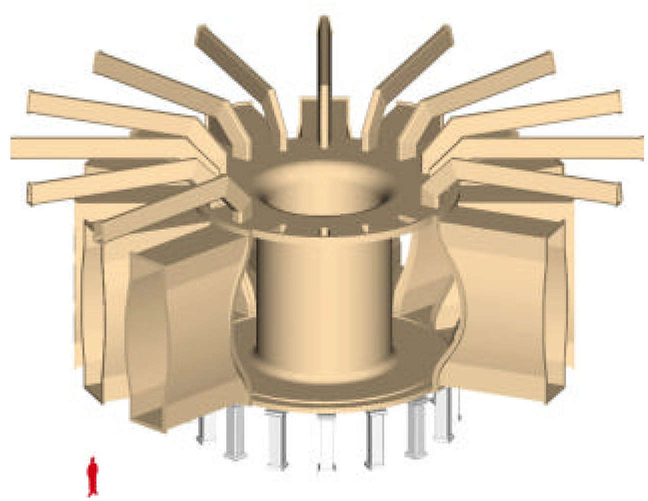
- **Provide and sustain a high level vacuum environment**
- **Serve as a gaseous tritium boundary**
- **Serve as an additional shielding and heat removal element**
- **Highly design dependent on power core configuration**
- **Close fitting to power core shielding to minimize internal volume and TF coil size**
- **Accommodate removal of coil sectors for maintenance (if sectors are removable)**
- **TF and PF coils are typically outside power core boundary, hence not cryogenic**

ARIES-AT

Cross Section of ARIES-AT Power Core Configuration



Cutout View of the ARIES-AT Vacuum Vessel



Vacuum Vessel contains main chamber, port enclosures, door assemblies, bulk shielding inside wall, and manifolding and plumbing

Summary of Direct Cost Accounts

Account 22.05.03 Vacuum Vessel (Historical Data)

Starfire and EBTR used the primary shields as a vacuum boundary (no vacuum vessel)

The ARIES studies used an algorithm for the cost of the ARIES vacuum vessel based on the mass of the vessel as shown below. Ron Miller documented and updated the coefficients for the ARIES designs due to a revised escalation basis

ARIES Designs	1992$ (LSA = 4)	2008$ (LSA = 4)
II-IV, SPPS, RS	$24 x VV mass in kg	$31.24 x VV mass in kg
AT	$26 x VV mass in kg	$37.10 x VV mass in kg

The ASC code also reported materials, volume fractions, fractional density, thickness and unit costs of 65.604/kg for inboard VV and $62.438 for all other VV components, but may have not been used

ARIES-AT	Vol, m^3	Mass, tonnes	1992$, LSA 4	2008$, LSA 4	2008$, LSA 1 (0.85)
$26/kg	295.12	1415.31	$36.80 M	$52.50 M	$44.63 M (used later for comparison)
$62.438/kg		1415.31	$88.37 M	$126.09 M	$107.15 M
$65.604		1415.31	$92.85 M	$132.48 M	$112.61 M

Since the ARIES ASC code reports a combined Vacuum System and Vacuum Vessel cost, currently these two costs cannot be separated except by the combined algorithm. Ron Miller is verifying the costs.

Also, it is not clear if the WC shielding balls are, or are not, included in the ASC costs.

Summary of Direct Cost Accounts

Account 22.05.03 Vacuum Vessel (Historical Data)

In 2006, Boeing conducted a detailed vacuum vessel design and cost study on the ARIES-AT design that provided the most current and extensive design and cost examination of a power plant relevant vacuum vessel. This vacuum vessel design used a double-walled ferritic steel (F82H) that was filled with water and tungsten carbide (WC) spheres as additional shielding materials.

Table X-5 ARIES-AT Vacuum Vessel Detailed Costing Study Results (steel only)

Component	2000$	2008$
Spool Assembly	$30.13/kg	$37.14/kg
Removable Doors	$44.36/kg	$54.68/kg
Door Frames	$76.12/kg	$93.82/kg
Port Enclosure	$30.26/kg	$37.30/kg
Composite Rate	$35.13/kg	$43.30/kg

Slightly lower than ARIES unit costs

Mass of the vacuum vessel was estimated to be 1,113.451 tonnes with a total cost of $39.115M (2000$) or $48.21M (2008$) without the cost of the WC shielding.

In comparison, ARIES-AT systems code data with $37.10/kg times 0.85 for an LSA = 1 plant and a calculated mass of 1415 tonnes would yield a cost of $44.63M. Although the costs are similar, the systems code calculated mass is much larger and the unit cost is lower with an additional LSA factor.

Summary of Direct Cost Accounts

Account 22.05.03 Vacuum Vessel (Historical Data)

The ITER Technical Basis Report documented the ITER vacuum vessel as a double-walled 316 LN stainless steel, cooled with water. The mass of the main vessel, port structures, ducts and 316 SS with boron shielding is 8448 tonnes. The preliminary ITER cost per the Snowmass cost analysis data scaled to 2008$ is $390.7M, which equates to $46/kg. LSA = 2? This is very comparable to the ARIES detailed estimate.

The FIRE vacuum vessel and ports weigh approximately 50 tonnes plus and additional 80 tonnes of SS shielding and are estimated to cost $63.43M in 2008$ per the Snowmass cost analysis data, which equates to $487/kg. Although this is for a smaller experimental machine, its cost estimate is quite high compared to the ARIES estimates. LSA = 2?

It is recommended that this composite rate of $43.14/kg (2008$) from the detailed ARIES-AT vacuum vessel study be adopted as the best cost basis for vacuum vessels (at LSA = 1) and a more accurate determination of the vacuum vessel mass be adopted for the computer code. This should include the cost of the main vacuum enclosure, the main ports for maintenance, ports for other purposes such as ECRH, and the vacuum doors for these ports. The cost of any boron carbide shielding spheres has to be added to this account, see the material cost rates for WC (~$33.78/kg in 2008$).

Summary of Direct Cost Accounts

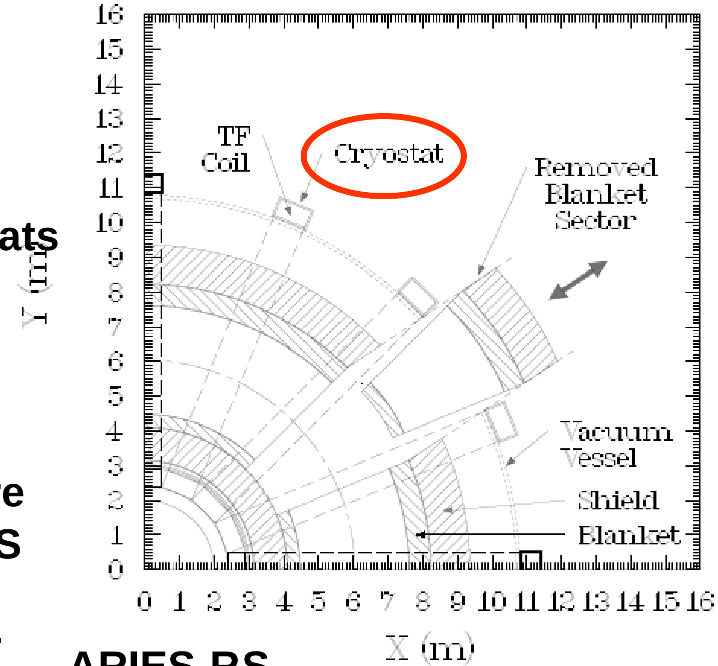
Account 22.05.04 Cryostat and Thermal Shield

Per the ARIES-II, -IV Fusion Reactor Report, Chapter 2 Systems Studies, ARIES-I, -II, -III, and -IV used a thin (5 cm) cryostat that completely enclosed the TF coils and each coil had a dedicated dewar. These reports did not indicate that either the cryostat or the dedicated cryostats or dewars were included in the cost of the coils.

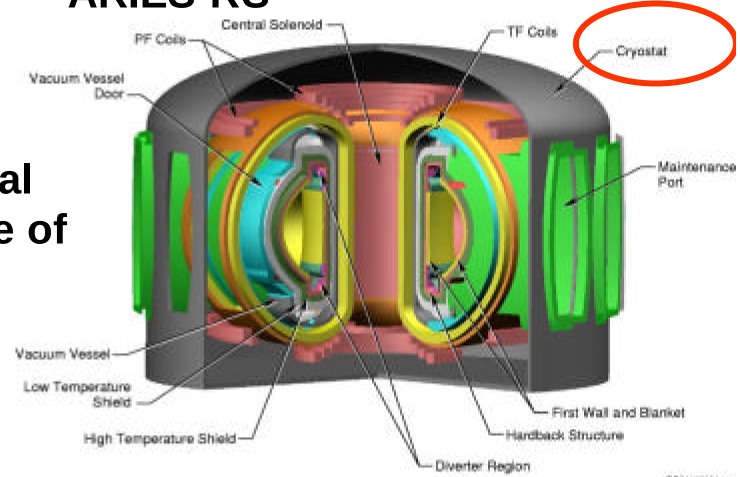
On the ARIES-RS and -AT, the concept of individual cryostats was not adopted and a much larger common cryostat was used. It was a domed, cylindrical structure that completely enclosed the power core. The ARIES-RS used double-walled, 304L SS sheets, except on the bottom. There is no active coolant, but uses multi-layer insulation.

The suggested RS material cost was \$35/kg (92\$) but it does not appear the cryostat is included in the structural cost. ARIES-RS ASC output reported a cryostat volume of 958 m^3 and mass of 1345 tonnes.

ARIES-1 to -IV



ARIES-RS

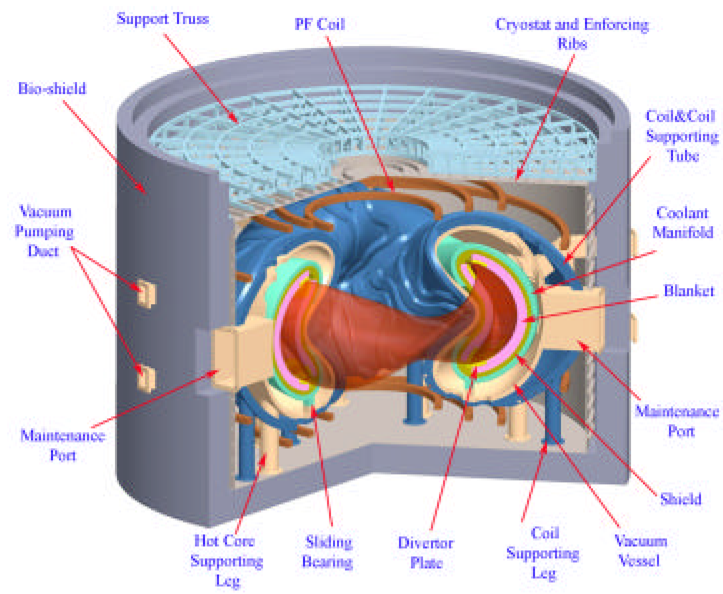


Summary of Direct Cost Accounts

Account 22.05.04 Cryostat and Thermal Shield (continued) ARIES-CS

From the CAD drawings, ARIES-AT concept used an identical cylindrical structure with a dome. But the cryostat volume and mass are only 7.88% of the RS data, namely 75.631 m^3 and 106.185 tonnes. The AT code summary sheet also listed a cryostat side volume of 34.773 m^3, but not sure what this meant or how it was used. There was no mention of the cryostat in the design book or in any of the technical papers. The cost of the cryostat did not seem to be included anywhere.

The ARIES-CS (Compact Stellarator, at right) adopted a different cryostat approach. It attached a thin steel sheet structure to the inner surface of the bioshield wall and floor. Above the power core, the cryostat was attached to the upper truss structure. The cryostat also had thermal insulating blanket. Also, it is not evident that this structure was ever included in the cost estimate.



It seems that the Cryostat and Thermal Shield structures have not been included in the ARIES cost estimates. The volume and mass of these structural elements should be computed and combined with appropriate unit cost to yield a viable cost and these costs included and identified in the cost estimate.

Summary of Direct Cost Accounts

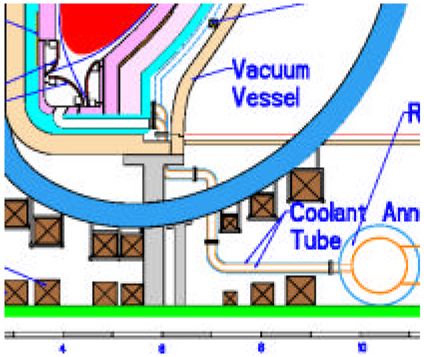
Account 22.05.05 Thermal Isolation Struts

The TF and PF coils are cryogenically cooled and need to be supported with thermal isolation supports. Various types of thermal isolation struts are used in all superconducting coil systems. Additionally, the hot power core structure needs to be supported and thermally isolated from support pedestal.

Starfire used twelve G-10CR glass-cloth/epoxy laminate to support the center-post.

ARIES-CS and ARIES-AT used both a cold support system for the coils and a hot support for the hot power core components primarily through the vacuum vessel structure.
ARIES-RS had support posts, but it appeared they supported the hot structure only.

ARIES-ST used normal conducting coils but it illustrated a complex support system to enable the bottom removal of the center post.



ARIES-AT Supports

Usually these thermal isolation struts are shown in the CAD drawings with varying degrees of fidelity, but loads, materials, and design details are not specified and no costs reported. These components should be better defined and their costs identified.

Summary of Direct Cost Accounts

Account 22.05.06 Common Dewar

In most fusion power plant designs, the superconducting TF and PF coils have individual cryogenic dewars around all their perimeter surfaces. Starfire decided to have a common dewar design for the inner TF coil legs combined with separate cryogenic dewars for the outer TF coil legs. They decided this would provide easier means to transfer the centering loads cryogenically and not have to transfer through warm structures if all the TF coils had individual dewars. This common dewar also provides much of the anti-torque capability for the combined structure.

This approach has generally not been adopted for fusion experiments or power plants.

Starfire provided a very detailed definition and costing of the common dewar approach. However, it is recommended ARIES does not define costing algorithms for this common dewar until such a common dewar design is adopted.

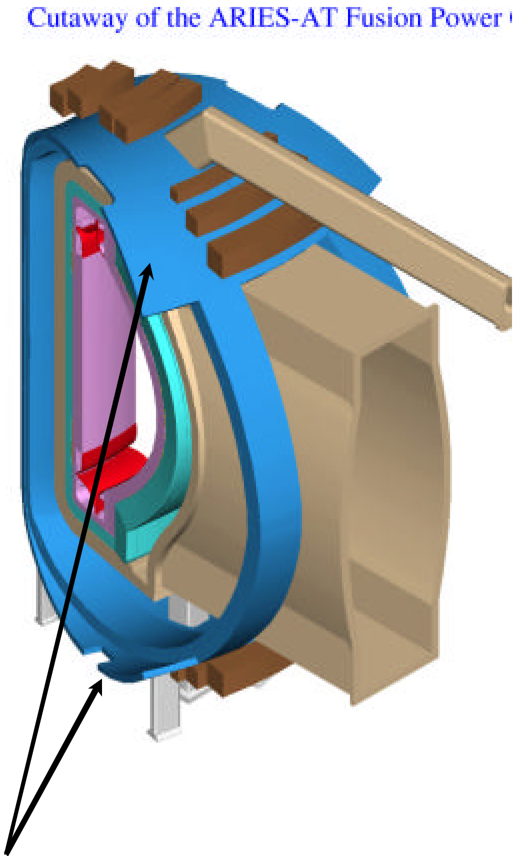
Summary of Direct Cost Accounts

Account 22.05.07 Anti-torque Structure

During operation there are forces on the TF coils that induce a torque on the coils, twisting them out of their plane. During certain off normal events the currents in the TF coils may be unequal and additional toroidal forces and torques may be applied to the TF coil cases that would cause additional toroidal deflections.

One method is to provide bridging structure between individual coils to counteract the induced torques. Starfire used this approach with shear panels.

Another approach is to connect the TF coils to a continuous restraining structure at the top and bottom of the coils, sometimes call a torque frame or structure. This structure is usually not used in the outer regions as maintenance and other power core access is required in that area. This approach was used in the ARIES-AT and in some other ARIES designs, but it has not been well defined and documented.



Carry through structure

These anti-torque structure components should be better defined as to the loads being transferred, materials specified, design details, and component costs.

Summary of Direct Cost Accounts

Account 22.05.08 Carry-Through Structure

Starfire identified this account but never actually had any components fitting into this category. It is probably a transition support structure that transmits loads from internal, high- or low-temperature, power core component down to the support pedestal.

It is recommended ARIES does not define costing algorithms for this carry – through structure until such a common carry-through structural design is adopted. This component may indeed be used once the structural design is better defined.

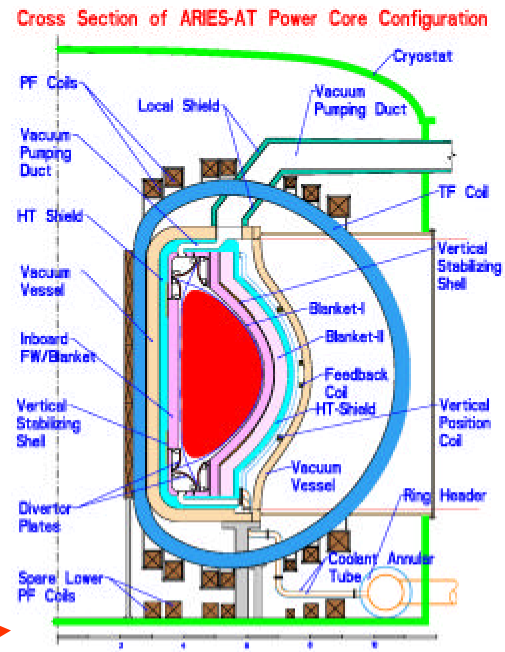
Summary of Direct Cost Accounts

Account 22.05.09 Structural Pedestal

This a structural element that supports the entire power core. It may be a single monolithic element or it may be a set of elements all attached to the building concrete floor. A single piece may be more efficient to deal with seismic events.

The Starfire report used a non-magnetic steel, Nonmagne 30, for the structural elements. This pedestal had a mass of 418.4 tonnes.

The ARIES designs typically do not identify any structural supports below the thermal isolation supports and rely on the concrete floor or base for structural support.



ARIES-AT

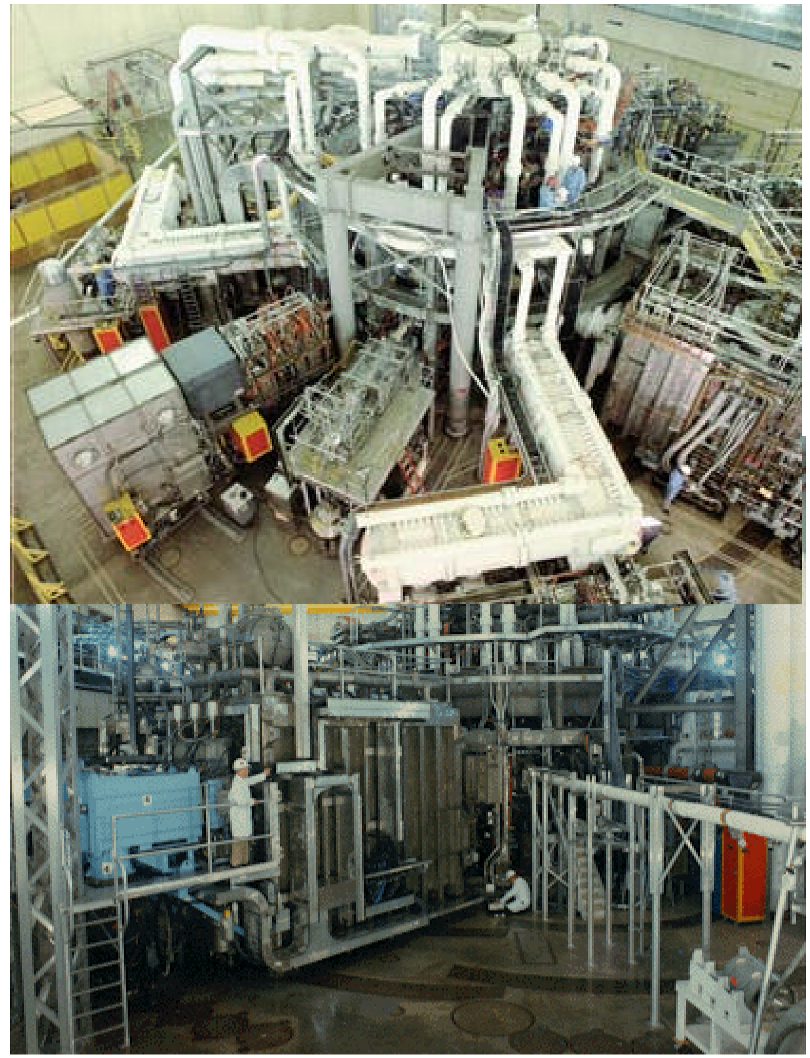
It is recommended ARIES does not define costing algorithms for this pedestal structure until such a structural pedestal design is adopted. This component may indeed be used once the structural design is better defined.

Summary of Direct Cost Accounts

Account 22.05.10 Equipment Support Structure

This is a general set of structural support elements for the ancillary equipment. This structure will include large support structures for neutral beam equipment and diagnostic equipment as well as small instrumentation equipment and wiring.

It is unrealistic to catalog all the ancillary equipment, so there will probably be a nominal allowance for this category.



TFTR

On to the Indirect Cost Algorithms

The following slides describe the development and evolution of the fusion indirect cost accounts including the interest and escalation during construction and the annual costs accounts with the methodologies to convert annual costs to cost of electricity elements.

The underlying financial assumptions are documented regarding the construction schedule, cash flow during the construction period, the methods to estimate the interest and escalation during construction, and the fixed charge rate.

The annual cost factors are also documented. Various authors, over a period of 30 years, contributed to this body of knowledge. But it is time to revisit those assumptions and evolved methodologies to see if they are the best method to compare fusion plant concepts to themselves and to the current and future competing power sources.

Makeup of Indirect Costs

As a part of defining all the fusion power plant cost accounts, Schulte, et. al. "*Fusion Reactor Design Studies – Standard Accounts for Cost Estimates*", PNL-2648, May 1978, prescribed the definition of the indirect cost accounts and some recommended values for use in conceptual fusion power plant studies. The specific indirect cost accounts are shown below with suggested allowances:

Acct 91, Construction Facilities, Equipment, and Services	**15% of Total Direct Cost**
Acct 92, Engineering and Construction Management Services	**15% of Total Direct Cost**
Acct 93, Owners Cost	**5% of Total Direct Cost**

This report referenced a prior Mc Donnell Douglas Astronautics report that compiled data from several then recent fission plants, TFTR, GA EPR, Wash 1230, and the UWMAK studies.

Makeup of Indirect Costs

L. Waganer, in the Starfire conceptual design study in 1980, developed a cost estimate for a more modular approach and standardized design to make the plant more affordable and quicker to build (6 years). This standardized design and modular construction with major assembly and checkout at an off-site location would also help reduce the indirect costs. He reduced the Construction Services to 10%, Engineering and Construction 8%, and Owner (or Other) costs were estimated to be 5% (function of direct capital costs). Thus the total indirect costs were reduced from 35% in the Schulte recommendation to 23% in Starfire. The ELMO Bumpy Torus Reactor and Power Plant, also estimated by Waganer, published in 1981 had a shorter 5-year construction schedule (higher degree of modularity) and retained the same indirect cost parameters as Starfire.

Acct	**Title**		**% of TDC**			
		Schlulte	**Starfire**	**EBTR**	**Generomak**	
	Constr Time, yr	Variable	6	5	8	6
91	Contstr Facil, Equip, and Serv	15	10	10	15	11.25
92	Engr and Constr Mgmt Serv	15	8	8	25	18.75
93	Owners Cost	5	5	5	10	7.5
	Total Indirects	35	23	23	50	37.5

Makeup of Indirect Costs

Many other following fusion conceptual design studies retained this costing methodology until the Sheffield and Delene Generomak papers reassessed many cost account bases and associated parameters. Sheffield recommended the construction time to be 8 years and the indirect costs increase to 15%, 25%, and 10% for a total indirect charge of 50%. Sheffield and Delene further proposed an indirect cost factor time-related algorithm in place of several separate indirect cost accounts:

Acct	**Title**	**% of TDC**				
		Schlulte	**Starfire**	**EBTR**	**Generomak**	
	Constr Time, yr	Variable	6	5	8	6
91	Contstr Facil, Equip, and Serv	15	10	10	15	11.25
92	Engr and Constr Mgmt Serv	15	8	8	25	18.75
93	Owners Cost	5	5	5	10	7.5
	Total Indirects	35	23	23	50	37.5

Six-data computed from provided algorithm

Influence of LSA on Indirect Costs

The Delene 1990 Generomak cost model update further modified the structure of the account by separating the accounts into four indirect accounts and linking the values to the Level of Safety Assurance (LSA).

The present ARIES costing uses Delene's and Miller's guidance for direct and indirect cost account values, indexed to LSA level. The table below lists all the indirect cost factors with subtotals and total factors from the recent ARIES-AT design. The table also includes contingency (that will be discussed shortly) and interest during construction (IDC). The Owners Cost is defined as 15% of the prior total direct and indirect costs per the previous Delene and Miller guidance.

	LSA = 4		**LSA = 3**		**LSA = 2**		**LSA =1**	
Account	Factors[a]		Factors[a]		Factors[a]		Factors[a]	
90 Direct Costs	1.00000		1.00000		1.00000		1.00000	
91 Con Serv & Eq	0.15100		0.12800		0.12000		0.11300	
92 Home Office Engr	0.05200		0.05200		0.05200		0.05200	
93 Field Office Engr	0.08700		0.06400		0.06000		0.05200	
Subtotal (ID costs)	**0.29000**		**0.24400**		**0.23200**		**0.21700**	
94 Owner's Cost (% D+ID ; % D)	0.1500	0.1935	0.1500	0.1866	0.1500	0.1848	0.1500	0.1826
Total Indirect Costs	**0.48350**		**0.43060**		**0.41680**		**0.39960**	
Total Dir + Indir costs	**1.48350**		**1.43060**		**1.41680**		**1.39960**	
95 Process Contingency	0		0		0		0	
96 Project Contingency (% D+ID ; % D)	0.1893	0.2808	0.1793	0.2565	0.1688	0.2391	0.1465	0.2050
97 Interest During Cnstr (% D+ID ; % D)	0.1652	0.29146	0.1652	0.27871	0.1652	0.27355	0.1652	0.26508
Total Overnight Costs	**2.05576**		**1.96581**		**1.92945**		**1.86968**	

[a] Factors are a ratio of indirect cost item to direct cost (90) unless noted (94, 96, 97)

Recommendation on Indirect Costs

Observing the ARIES total indirect costs (as defined by Accounts 91, 92, 93, and 94), the ARIES indirect costs are below the 50% level recommended by Schulte and above the 23% level used by Starfire conceptual design study.

It cannot be determined if ARIES has another factor linked to construction time, but it is not evident that Accounts 91, 92, and 93 have any time related influence. Owners Cost might have some time related costs, such as insurance.

It is recommended that we retain the present ARIES indirect cost scaling (as shown in the previous table) and continue linking to both direct and indirect costs to the four LSA factors. The indirect costs and LSA factors should be revisited in the future when GEN IV indirect costs are quantified.

Handling of Contingency

Per Schulte, et al, contingency allowance is for unforeseen or unpredictable expenses that might be incurred during facility construction and startup. (Project) Contingency should reflect any cost uncertainty resulting from potential acts of nature and non-design related construction problems. Uncertainties from technical design (Process Contingency) should be accounted for in design allowances, which should be resolved by the 10th of a kind plant.

In 1989, a report by Schulte, et al. on standard unit costs for fusion reactor studies recommended 15% of accounts 21 through 25 be provided to account for unforeseen expenses. Starfire adopted these guidelines at 15%, but included within each of the specified accounts (21-25) and omitting the cost of spares.

Generomak, Sheffield and Delene, did not address project contingency in detail, instead chose to continue to use an all-inclusive contingency allowance of 15% added to all the plant direct costs. Then the Delene 1990 Generomak cost model update altered the contingency allowance to reflect changes relative to the LSA level and redefined the project contingency to be a fraction not only the total direct cost but also the indirect costs (Accounts 91, 92, 93, and 94). Their recommended contingency factors were: 0.195, 0.184, 0.173, and 0.15 for LSA =4 through 1. Although the LSA 1 factor (0.15) remains numerically the same as the prior guidance, the inclusion of the indirect costs effectively increases the contingency amount by 40% to 50% per the total indirect costs shown on the previous table. ARIES has adopted this approach although there is a slight difference in values.

Handling of Contingency

The more recent Gen IV cost estimating guideline addressed contingency very completely, including contingency on overnight costs, contingency on schedule impact, and contingency on reactor performance. As opposed to the fusion approach that contingency excludes design and performance uncertainties and focuses only on external uncertainties, the Gen IV has the opposite approach. It includes an allowance for indeterminate elements and is related to the level of design, degree of technological advancement, and the quality/reliability pricing level of given components. This would appropriately equate to a sizable contingency for the prototype, demonstration, and first of a kind (FOAK) plant, as opposed to a low contingency for an n^{th} of a kind (NOAK) plant. This is exactly opposite to the philosophy adopted by Schulte, Starfire, and ARIES.

The allowance for contingencies is a very controversial topic. On prototypical and early developmental plants, significant contingencies are certainly required for design changes, schedule extensions, and changes necessary to achieve performance goals, reflective of the Gen IV guidance. On the other hand, contingencies for NOAK plants would likely be much lower and be related to outside influences, more aligned with the Schulte's and Delene's guidance. ARIES should develop a recommendation on project and process contingency.

Plant Construction Financial Costs

The prior direct and indirect costs are considered to be the Overnight Costs.

This section on Plant Construction Financial Costs addresses the assumptions, methodologies and algorithms associated with the financing of the procurement and construction of the plant and its facilities. These factors consider the cash flow necessary to procure and construct the facility, any inflationary effects on the cash flow, and the accrual of interest and other factors charged to the incremental cash flow.

Defining Cash Flow

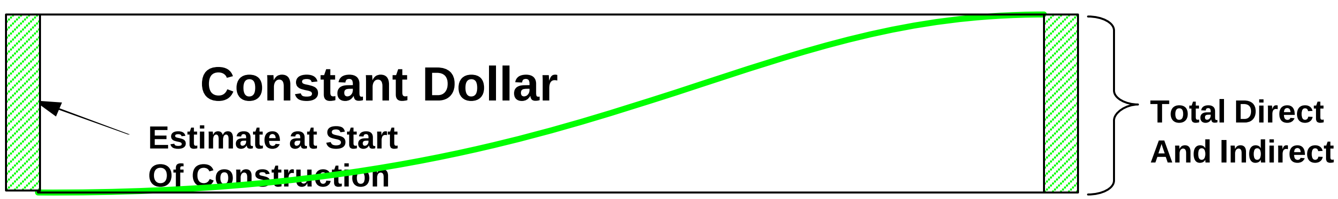
The expected distribution of the cash flow during the construction period would not be a continuous function; rather it would be composed of many unequal step functions. For simplicity, estimates for conceptual and preliminary design studies assume a smooth and continuous skewed "S"-shaped expenditure curve. The "S"-shaped expenditure curve was postulated by NUS Corporation in NUS-531 with 50% of the cash flow occurring at 60% of the construction time. D. Phung further developed the methodology by developing the payout function and integrated payout function for the skewed S-shaped curves, as follows.

Payout function: $p(t) = 0.5\ a\ p\ /B\ (t/B)^{(a-1)} \sin[p\ (t/B^{a}]$

Integrated payout function: $q(t) = 0.5[1-\cos[p\ (t/B^{a}]]$

Factors:	**a is the skewness parameter; if < one, the payout is skewed to the left,**
	If a is > than one, the payout is skewed to the right (most likely case).
Derivation,	**a = ln(0.5)/ln(0.6), where numerator is 50% of cash flow,**
	denominator is percentage of time when 50% of cash flow is achieved.
	For a – 1.357, half the cash flow is achieved at 60% of the construction period.
	B is the construction time in periods of appropriate to the analysis
	t is the incremental time parameter

During the conceptual Starfire design, L. Waganer adopted the right skewed "S" curve cash flow and further refined the accuracy of the data provided by Phung.



Defining Cash Flow

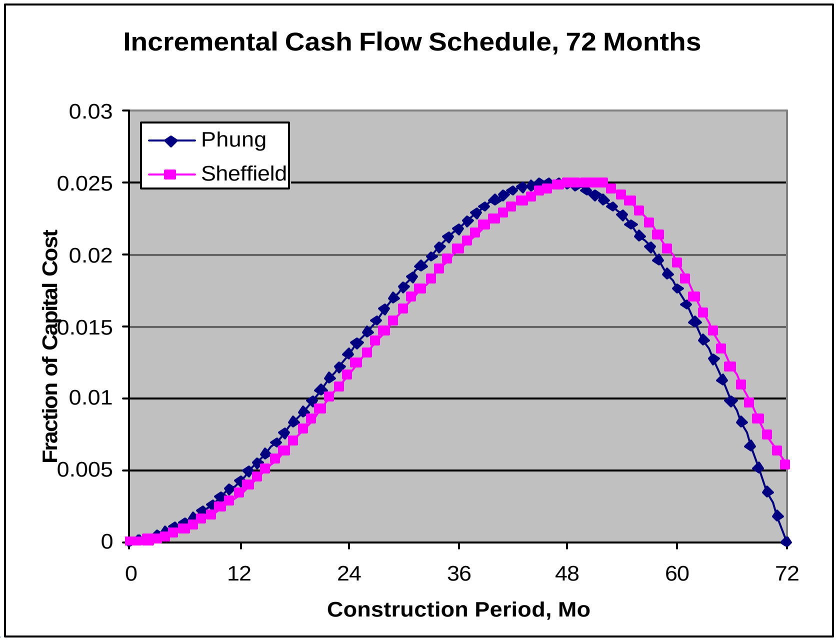
Sheffield and Delene further modified the modeling of these financial analyses with the use of a generic fusion plant model with more detail involving taxes, insurance and depreciation during the construction period. Sheffield chose to modify the shape and modeling of the cash flow curve distribution with the peak spending slightly later (62.5%). In that formulation, two separate equations were defined for the early phase and the later phase of the construction schedule.

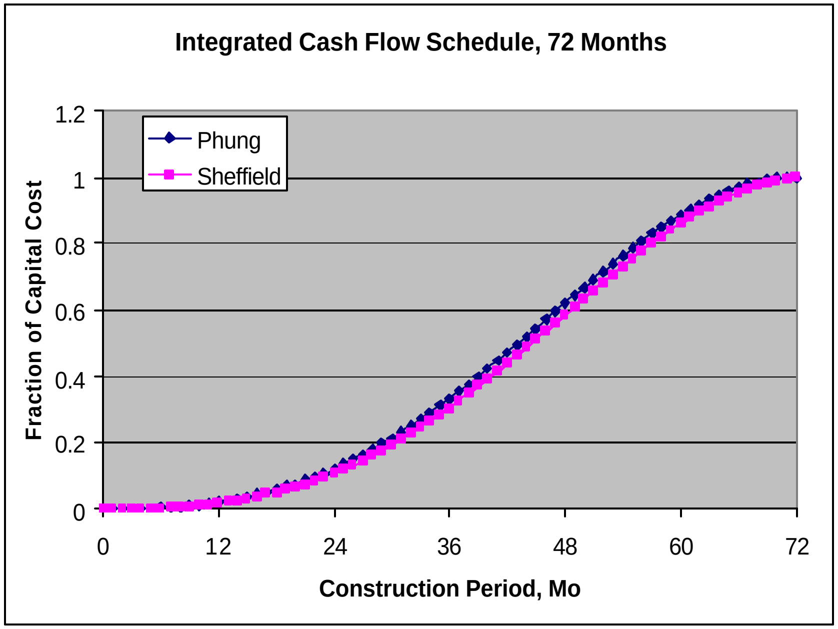
P(?) = A [sin(? -90º)+1.0]   for ? between 0 º and 180º

= A [0.95 sin(1.7 ? +144º) + 1.05   for ? between 180º and 257.1º

Where j is the time step period, ? = j (257.1/B)º and A = $_{j=1}$? ^{B} p(?)

Ron Miller has not determined which curve is being used for cash flow in ARIES.





Defining Cash Flow

The Economic Modeling Working Group (EMWG) of the Generation IV International Forum has recently updated their “Cost Estimating Guidelines for Generation IV Nuclear Energy Systems” in September 2007, Rev 4.2. Several key guidelines are relevant to the methodology for fusion economic studies were identified. The Gen IV EMWG specified the use of an S-shaped cash flow expenditure curve. However the skewness and algorithm for curve generation was not specified.

It is recommended for ARIES to adopt the traditional cosine or “S”-shaped cumulative cash flow curve defined by the Phung integral equations. These are continuous functions, not discontinuous approximations. The time period is easily adjusted. Moreover, the entire curve can be skewed to the right or the left by changing the “a” skewness parameter as desired. Using the integral forms, many discrete steps can be summed to approximate the integral functions.

Defining Time Value of Money

At the start of construction, the total overnight costs have been identified necessary to procure and construct the plant. However, the plant cannot physically be procured or constructed overnight and requires some elapsed time for this process to be financed and completed. The prior section identifies a prescriptive cumulative cash flow curve necessary to complete the project. There are two primary time-related analysis approaches that determine the total cost necessary at the end of construction:

- **Escalation due to inflationary effects from the start of construction and**
- **Interest compounded from the date of cash accrual to the start of plant operation.**

Defining Time Value of Money

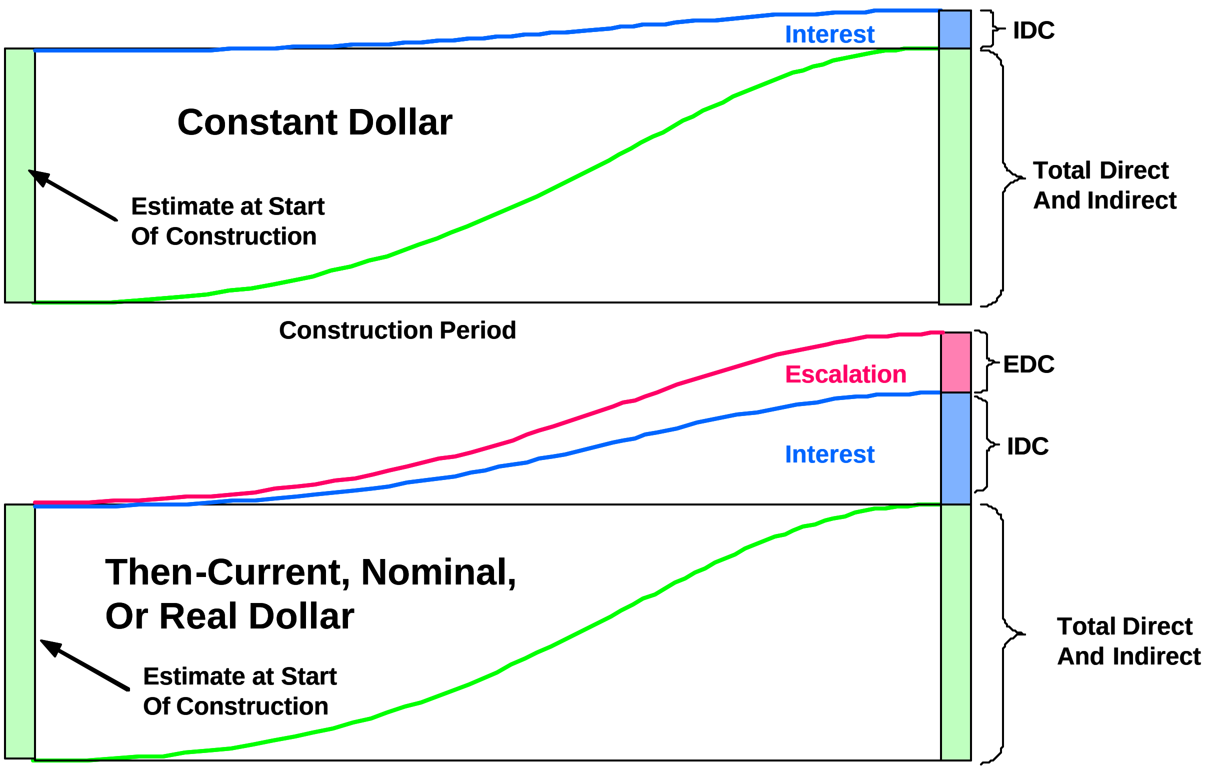
There are two methodologies defined by Phung to evaluate the time-related effects that occur during the construction period:

- **"Constant Dollars" defined by Phung, which assumes the purchasing power of the dollar remains constant throughout the construction period. Therefore, there is no inflation. However, there are costs associated with the true (or real) interest value. This will not be a realistic situation in the actual world as there are always inflationary (or deflationary) effects, but this "Constant Dollar" analysis provides a more easily understood economic metric that avoids making the assumptions about future inflationary/deflationary effects. The rate of interest is usually in the range of 3 to 6% without inflation. Cumulative interest is accrued throughout the construction period and is called Interest During Construction (IDC). The Interest During Construction (IDC) is dependent on the cash flow curve.**

- **The second methodology is called "Then-Current Dollars" or "nominal dollars". This is the cost for an item measured in as-spent dollars and includes inflation effects. This analysis mode includes both escalation (related to inflation) and interest. This factor is called Escalation during Construction (EDC). The interest rate, when stated in current or nominal dollars, inherently includes an escalation factor. The total capital investment required at the end of construction = initial capital investment x (1 + IDC + EDC) with appropriate interest and escalation rates applied over the cash flow schedule.**

Defining Time Value of Money

The Starfire economic analysis, conducted by Waganer, was probably the first conceptual fusion reactor design study to adopt the concept of constant and then-current dollar and cash flow financial analyses. Below is a reproduced Starlight graphic that illustrates the differences between constant and then-current dollar analysis. In the Starfire economic analysis, the constant dollar interest was 5% (IDC = 0.1303) and in the then-current dollar analysis the escalation (inflation) was 5% (EDC = 0.1896) and inflated interest was 10% (IDC = 0.3164).



Definition of IDC and EDC

Phung formulated the equations for the total investment at the end of construction (start of operation):

$$I(t_{co}) = {}_1?^{B}\ I(t_b)\ p(t)\ (1+y)^t\ (1+x)^{(B-t)}\ ,$$

where p(t) is the continuous function of t, y is the inflation rate, and x is the interest rate.

Waganer called this additive factor to be the f_{EIDC} factor to indicate the summation of both the IDC and EDC in the then-current dollar mode.

Phung further formulated the equations that separated the EDC and the IDC integral functions and provided tabular data that identified the relationships between the construction time (B), the interest rate (x) and the escalation rate (y):

$$f_{EDC} = [{}_0?^{B}\ p(t)\ (1+y)^t\ dt]\ \text{, and}$$

$$f_{IDC} = [{}_0?^{B}\ p(t)\ (1+y)^t\ (1+x)^{B-t}\ dt]\ -\ [{}_0?^{B}\ p(t)\ (1+y)^t\ dt]\ \text{and,}$$

$$1 + f_{EDC} + f_{IDC} = (1+x)^B\ [{}_0?^{B}\ p(t)\ ((1+y)/(1+x))^t\ dt]$$

Delene and Sheffield used these Phung methodology in their Generomak model with quarterly time increments. However, in the Sheffield Fusion Technology paper, rather than evaluate the integral equation, Sheffield developed an approximate solution, shown below.

$$F_{cap-1} = F_{EIDC} \sim [1.0840 + 0.55(y-0.09) + 0.38(x-0.09)]^{B+0.6}1\ \ -1$$

Ron Miller will verify if the ASC code used the more formal integral expressions for the determination of the ARIES IDC and EDC factors. ARIES has expressed all of their economic estimates in both constant and then current (nominal) dollars (1992$).

Definition of IDC and EDC

The Gen IV guidance is that only the constant dollar analysis approach should be used. Their pricing basis is currently in 2007 dollars. The Gen IV IDC model in constant dollars is essentially the same as the prior Phung expression for IDC.

After reviewing these methodologies, all of them are really derived from the original Phung expressions. Sheffield used approximation methods to calculate the S-shaped cost flow schedule and the IDC/EDC factors. It is recommended ARIES affirm its usage of the skewed S-curves and the integral forms of the cash flow calculations. It is recommended that ARIES primarily use the constant dollar valuation methodology consistent with Gen IV direction. Then-current dollars can be included if desired.

Interest and Escalation Rates

The 1978 PNL report defined a methodology for handling time related costs using the constant and then-current dollar analyses. They recommended an interest rate of 5% for the constant dollar case and an interest rate of 10% and an escalation rate of 5% for the then-current dollar case. Starfire used the same methodology and data.

Generomak originally assumed a real interest rate of 3% in the constant dollar analysis and an escalation rate of 6% and an interest rate of 9% in the current year analysis for an 8 year construction period.

In 1989 J. Delene updated the Generomak model and increased the capacity factor from 65% to 75%, reduced the escalation rate from 6% to 5%, and changed the average cost of money from 5.1% and 11.4% to 6.05% (without inflation) and 11.35% (with inflation), respectively. He noted the US Tax Reform Act of 1986 decreased the federal tax rate from 45% to 34%. Thus, the AFUDC must use the average cost of money rather than the tax-adjusted cost of money, which is 9.7% nominal and 4.35% constant or real. The ARIES ASC code is currently using the 6.05% (without inflation) and 11.35% (with inflation) average cost of money for its IDC and EDC computations.

The Gen IV guidance is that only the constant dollar analysis approach be used in 2007$ and the GDP Price Deflator is the measure of inflation and escalation.

The recommendation is to adopt the GEN IV simplified approach with only constant dollars with the average, real cost of money (interest) to be 5% for regulated utility customers and 10% for deregulated or merchant plant customers. This eliminates the need to estimate future tax rates, tax incentives, and other cost of money effects. See table on the next page for impact.

Interest and Escalation Rates Compared

The Table below compares the differing methodologies and assumptions on interest and escalation. The reference data is shown in black and the code results are shown in green.

Waganer wrote an Excel spreadsheet (ESC) that computes the Phung equations with 1000 time steps and it matches the Starfire data.

Generomak, with preliminary interest and escalation values, matches reasonably well, usually to the second or third significant digit. Later Generomak and ARIES data does not match so well. (We still need to determine the cause of the differences.)

If ARIES adopts the constant cost of money cost of money approach, the regulated utility costs will be lower, but the de-regulated utility costs will be increased from the current ARIES estimates.

Table X1. Comparison of AFUDC Approaches and Results

	Phung		Starfire		Generomak1986		Delene 2001		ARIES II-IV		Gen IV	
	Constant	Nominal	Constant	Nominal	Constant	Nominal	Constant	Nominal	Constant	Nominal	Constant	Constant
Interest	0.05	0.10	0.05	0.10	0.03	0.09	0.0634	0.0953	0.0605	0.1135	0.05	0.10
Escalation	0.00	0.05	0.00	0.05	0.00	0.06	0.00	0.03	0.00	0.05	0.00	0.00
Constr Time	6		6		6		6		6		6	
IDC	0.1300	0.3160	0.1303	0.3163	0.0750	0.2440	0.2196		0.1652	0.3178		
Cmptd IDC	0.1303	0.3164	0.1303	0.3164	0.0766	0.2309	0.1675	0.2835	0.1594	0.3640	0.1303	0.2744
EDC	0.0000	0.1900	0.0000	0.1896	0.0000	NA				0.2630		
Cmptd EDC	-	0.1896	-	0.1896	-	0.2309	-	0.1105	-	0.1896	-	-
EIDC				0.5059		0.5240						
Cmptd EIDC	0.1303	0.5060	0.1303	0.5060	0.0776	0.5208	0.1675	0.3940	0.1594	0.5536	0.1303	0.2744

Annual Cost Calculations

The busbar cost of electricity is the most important considerations for utilities or independent power producers in choosing an electrical generating power plant. The plant must be an affordable, reliable, maintainable energy source and all of these factors are contained in the cost of electricity. The busbar cost of electricity is given by:

$COE = [C_{AC} + (C_{O\&M} + C_{SCR} + C_F) * (1 + y)^Y]/(8760*P_E* p_f) + C_{D\&D}$, where

- C_{AC} is the annual capital cost charge (total capital x FCR)
- $C_{O\&M}$ is the annual operations and maintenance cost
- C_{SCR} is the annual scheduled component replacement cost
- C_F is the annual fuel costs
- y is the annual escalation rate (0.0 for constant dollar and y for current dollar)
- Y is the construction and startup period in years
- P_E is the net electrical power (MWe)
- p_f is the plant capacity factor (~ plant availability)
- $C_{D\&D}$ is the annual decontamination and decommissioning converted to mills/kWhr

I will address each of these Annual Cost Accounts in sequence

Annual Capital Cost

The annual capital cost charge is determined by applying a fixed charge rate (FCR) to the total capital cost of the power plant.

The genesis of the fusion definition of a fixed charge rate (FCR) stems from the NUS Guide for Economic Evaluation of Nuclear Power Plant Design. Schulte elaborated on the fixed charge rate in the Fusion Reactor Design Studies – Standard Accounts for Cost Estimates report in 1978.

The fixed charge rate is a charge to total investment costs that is annualized over the operating life of the plant. Schulte included the cost of capital, depreciation, interim replacement, property insurance, and federal and state taxes for both constant and current (nominal) economic analysis approaches. The assumed annual fixed charge rate was 10% for the constant and 15% for the current dollar analysis approach. The costs of large replacement items (greater than $10,000) were excluded from the assumed allowance and would be treated as a separate annualized expense. Starfire used the same methodology and data as the Schulte guidance.

Annual Capital Cost

Sheffield and Delene, "Cost Assessment of a Generic Magnetic Fusion Reactor", adopted the economic and financial parameters from the Nuclear Energy Cost Data Base (NECDB) to establish a FCR to calculate the annualized capital cost charge. Their analysis involved tax rates, depreciation, salvage value, cost of money and construction period. The steady state FCR was determined by numerically integrating over the first 20 years (not the entire operating period). The levelized FCR was determined to be 0.1652 in current dollars and .0998 in constant dollars.

In a refinement of the Generomak cost modeling, Delene and Sheffield adopted a 6-year construction and startup period in place of the prior 8-year construction period and amortized the capital cost over the entire plant life of 30 years. They determined that the AFUDC is an imputed return on capital and is not applicable to tax credits or tax depreciation. The resulting FCR only slightly differed from the prior analysis, namely 0.165 for the current dollars and 0.0844 for the constant dollar analysis.

In 1989, Delene updated the FCR, based on revised NECDB methodology, revised federal tax code changes (34%), and higher cost of money. This resulted in a revised FCR of 0.0966 in constant dollars.

The ARIES II-IV Systems Studies followed the Delene Generomak updated FCR using the book life equal to the analysis period. The FRC value remains at 0.1637 in current dollars and 0.0965 in constant dollars for ARIES II-IV through ARIES-AT. The ARIES construction time is 6 years and the economic plant life is 30 years. Note that the current ARIES-AT life of plant components is 40 full power years. Economic life would be FPY/availability ~ 44.4 years at 90% availability.

Annual Capital Cost

The Gen IV guidance takes a much more simplified approach in that tax and depreciation considerations are not considered at present. This formulation is much easier to compare to other power generation systems in other countries.

FCR = X/[1-(1+X) $^{-Lecon}$] ,

where X is real discount rate of 5% and 10% in constant dollars,

and L_{econ} is the economic or regulatory life of plant (years)

The Gen IV assumes a 40-year economic and regulatory life, resulting in FCR values of 0.05828 for the 0.05 discount rate and a FCR of 0.10226 for the 0.10 discount rate (ARIES values are 0.0965 in constant dollars and 0.1637 in current dollars) .

It is recommended that the Fixed Charge Rate (FRC) of the Gen IV formulation be adopted because of the simplified approach of not considering the changing aspects of the tax laws and depreciated assets. The use of the standardized constant year cost of money at 0.05 and 0.10 should be adopted.

This approach will effectively halve the annual capitalization factor (0.0583 compared to the ARIES value of 0.0966) for the 5% COM case and raise the 10% COM case slightly above the current ARES capitalization factor (0.1023 compared to 0.966) for the constant dollar analysis. This capitalization factor is responsible for ~ 75% of the cost of electricity. Therefore the ARIES COE will fall to roughly to half its current value. ARIES should also go to a 40-year economic life to be consistent with its technology baseline. This lifetime is also consistent with GEN IV lifetime. This extension of the economic life will slightly lower the FCR.

Annual Operations and Maintenance Costs

The UWMAK-I study, 1974, had a detailed description of O&M accounts and costs. In 1978, Schulte also established the annual O&M accounts, including:

- **salaries,**
- **supplies and equipment,**
- **outside support services,**
- **general and administrative costs,**
- **coolant makeup,**
- **fuel handling costs, and**
- **miscellaneous costs.**

He suggested an allowance of 2% of total direct and indirect costs, but not including the time related costs (Accounts 94 and 95).

Waganer, in Starfire, adopted the same Schulte scheme, but chose to estimate the O&M costs in a bottoms-up approach, much like UWMAK-1. It assumed the fusion plant would be more highly automated than traditional fission plants, thus a full staff would only require 153 people, not counting security personnel. The Salaries cost (Account 40) would be $8.71M in 1980$ or $19.86M in 2008$.

Table X-4 Starfire O&M Costs

	1980$	2008$
Acct 40. Salaries of Facility Personnel	$8.71M	$19.86M
Acct 41. Annual Misc Supplies and Equipment	$5.2M	$11.86M
Acct 42. Outside Support Services	$0.792M	$1.806M
Acct 43. General and Adm (15% of Accts 40, 41, 42)	$2.205M	$5.027M
Acct 44. Annual Coolant Makeup (water)	$0	$0
Acct 45 Annual Process Materials	$1.00M	$2.28
Acct 46 Annual Fuel Handling (handled by staff)	$0	$0
Acct 47 Annual Miscellaneous	$1.50M	$3.42M
Totals	$19.407M	$44.25M

Annual Operations and Maintenance Costs

Sheffield and Delene, in the Cost Assessment of a Generic Magnetic Fusion Reactor, recommended that the number of the operating staff be significantly increased from the Starfire staff of 153 to 457 following a study of fission plants. Starfire had a 5-shift operation and Generomak assumed a 6-shift operation. Other than the increased staff, the Starfire O&M costs were generally adopted.

The total O&M annual cost was estimated to be $49.1M (1983$) or $92.8M (2008$)(for a 1200 MWe plant) or approximately double the Starfire estimate. When converted to annual COE contribution, O&M amounted to 7.7 mills/kWh (with appropriate plant capacity, availability and so on). This report suggested a general O&M scaling rule of:

$$C_{O\&M} \text{ (mills/kWh)} = 7.7 * (1200/P_e)^{0.5}.$$

In the subsequent refinement of the Generomak cost modeling, Delene updated the costing of the earlier Generomak study in 1983$ to 1990$. The O&M costs increased from $49.1M to $74.4M for an LSA = 4 and $68.82M for LSA= 3 in 1990$. He also expressed the O&M cost to be related to P_e as follows:

$$C_{O\&M} \text{ (annual cost)} = \$74.4M * (P_e/1200)^{0.5} \text{ (in 1990\$)}.$$

When normalized back to a 1000 MWe plant and scaled to 2008$, the annual O&M cost will be $102.60M (2008$). However this reflects an LSA = 4 plant. Delene suggested factors of 0.70, 0.85, 0.925, and 1.00 for LSAs of 1, 2, 3 and 4.

Annual Operations and Maintenance Costs

The stated ARIES algorithm for $C_{O\&M}$ (in M$/y) = $74.4M*(PE/1200)0.5. Since all costs in the ARIES reports are reported in 1992$, it was inferred that this constant was also in 1992$. But really, it is not. Instead it is reflecting the Delene algorithm quoted in 1990$. Perhaps it should be $78.77 M (1992$).

The O&M costs are identical in ARIES-RS with the same GDP Price Level Deflator values for 1990 and 1992 (9.16 mill/kWh in 1992$). The data for ARIES – ST had slightly different GDP deflator data and when the O&M costs were adjusted using the different GDP data, the O&M costs were nearly identical (9.29 mills/kWh reported vs. 9.2736 mills/kWh calculated).

The ARIES-AT also had different GDP data, a higher availability of 0.85 as compared to 0.7589, and an LSA = 1. With these revised data inputs, the predicted O&M was slightly lower than reported, 6.87 mills/kWh (LSA=1)vs. 6.819 mills/kWh calculated. This is less than 1% error, but something is not being computed correctly. The reported O&M COE cost of 6.87 mills/kWh corresponds to an annual O&M cost of $51.15M (in 1992$) or 72.99M (in 2008$).

Annual Operations and Maintenance Costs

The Gen IV guidance assumes no escalation in the analysis, so the O&M estimate at the start of construction will be the same as when operation starts, that is the constant dollar case. The accounts identified are somewhat different, but the content is virtually the same. The categories of staff are identified along with suggested costs per staff member for 2007$. These are provided for a bottoms up estimate. These data would be helpful to update the ARIES fusion database with our current thoughts on staffing levels.

For the top-down methodology, the GEN IV EMWG adopted a levelized O&M algorithm that combines both fixed and variable costs, based on operating LWRs taken from IAEA data.

For a 1000 MWe plant, A = 0.90

	Annual Cost (2007$)	COE Component (2007$
Fixed O&M cost	$62M	7.85 mills/kWh
Variable O&M cost	$3.55M	0.45 mills/kWh
Total	$65.5M	8.30 mills/kWh

Although not stated, it is presumed that the fixed O&M cost would be scaled to plant size by some factor, such as $62M *(Pe/1000)$^{0.5}$ while the variable costs would continue to scale with the produced power in kilowatt-hours. The $65.5M in 2007$ would be $67.47M in 2008$.

Annual O & M Costs

The O&M cost estimates seem to be all over the map with costs dependent on total direct and indirect costs (Schulte), two attempts at bottom up estimates (Starfire (Waganer) and Sheffield), and single expression scaled to net power and LSA level. All of these estimates span a period of time approximately 30 years. All the ARIES studies were reported in 1992$. Table X-5 below takes all the original O&M costs (sometimes backed out of the O&M COE data) and normalizes all of them to 2008$ for a scaled 1000 MWe reactor. Availability values do not enter these data except to convert COE values back to absolute costs. If the data is sorted by LSA, the data begins to group in a more logical fashion. This is because ARIES has adopted the LSA scheme, which baselines the costs for an LSA of 4 and reduces O&M costs to 70% for the LSA 1 value.

Table X-5 Summary of Historical O&M Cost from Tokamak Studies and GEN IV

						2008 M$ for 1000 Mwe			
Study	**LSA**	**Avail**	**Orig Pe**	**Orig M$**	**Year$**	**LSA 1**	**LSA 2**	**LSA 3**	**LSA4**
Schulte	~3	0.65	1000	38.57	1978$?			103.90	
Starfire	~3	0.75	1000	19.41	1980$			44.26	
Sheffield, Gnrmk	~2	0.76	1200	49.10	1983$		84.72		
Delene, Gnrmk	1,2,3,4	0.76	1200	74.40	1990$	71.82	87.21	94.9	102.6
ARIES-II (92)	2	0.76	1000	60.98	1992$	71.66	**87.01**	94.69	102.36
ARIES-IV (92)	1	0.76	1000	50.20	1992$	**71.62**	86.97	94.64	102.31
ARIES-RS (96)	2	0.7589	1000	60.90	1992$	71.56	**86.89**	94.56	102.22
ARIES-ST (99)	2	0.7589	1000	61.69	1992$	72.49	**88.02**	95.79	103.55
ARIES-AT (00)	1	0.85	1000	51.15	1992$	**72.99**	88.63	96.45	104.27
GEN IV		0.90	1000	65.5	2007$			67.47	67.47

Annual O & M Costs

If the philosophy that the operations and maintenance costs are determined by either the capital costs (which are determined by LSA capital cost factors) or by staffing, supplies, materials, services being determined by the influence of LSA, then the LSA scaling should be continued per the current ARIES approach.

In lieu of new technologies in staffing large facilities, it is recommended that the bottoms up approach be revisited to help baseline any adopted simplified algorithms, especially in facility staff and salaries.

Scheduled Component Replacement Costs

Schulte foresaw the need to identify and monitor the cost of those high cost power core components that have a limited life less than the economic life of the plant, especially the first wall and blanket modules, divertor modules, and heating and current drive. In certain magnetic configurations, other components might be in this costly replaceable category, such as an internal, unshielded TF coil element.

Schulte did consider disassembly and reassembly labor to be in this account. In the constant dollar mode, no escalation is considered, so the annual cost is represented by the initial cost of the components divided by their lifetime with plant availability included. In the constant or nominal dollar mode, the annual costs are multiplied by the escalation factor, $(1+y)^B$.

Schulte did not specifically include the initial set of power core components in this category as they should be capitalized along with the other direct capital costs that are necessary for testing and initial operation for some period. Waganer, in Starfire, also adopted this approach and identified the components to be replaced and that replacement time interval as a part of the plant availability. All subsequent replaceable component hardware would be included in the Scheduled Component Replacement (SCR) cost account.

This precept was challenged by Sheffield, et al., in Generomak because they felt the initial set of components should be integrated with the annual cost accounts.

Later, Bathke and Miller in the ARIES II, IV reactor studies, agreed with Schulte and Waganer that the initial set of hardware should be capitalized in the initial direct capital cost accounts otherwise it would tend to underestimate the initial capital cost of the power core. This approach continues in the current ARIES cost models.

SCR Labor Costs

Waganer, in Starfire, assumed the labor associated with disassembly and reassembly would be highly automated and would be a part of the duties of the regular plant staff. If SCR only occurred on a regularly basis, this might be handled with contract labor. However, when an unscheduled failure occurs, it is necessary to immediately accomplish the repair, it becomes more likely the on-site staff would provide the required labor. This logic persists through Generomak and ARIES cost estimates.

Combining Fuel and SCR Costs

Schulte created separate accounts for both SCR and Fuel. Schulte considered all fuel materials in this category, such as deutritium, tritium, liquid breeders or multipliers and other fuel materials, for instance, advanced fuel materials. However Schulte did not include the cost of the containing elements, such as the blankets or divertors to be a part of the fuel cost account. Waganer in Starfire continued that approach.

Sheffield, et al, "Cost Assessment of a Generic Reactor" chose to aggregate the Scheduled Component Replacement items with the Fuel Cost. Sheffield had a very complex formula to determine the component cost accounting for radiation damage limits, wall loading, plant availability, spares, and a cost recovery factor.

Delene supported the Sheffield approach in that he thought the SCR cost items should be in the Fuel Cost account and be treated as a present worth item producing a revenue stream over their lifetime, with lifetime, depreciation, taxes, cost of money, and capital recovery factors used.

Bathke and Miller in ARIES II-IV study reverted back to separately identifying both the SCR and Fuel cost items. They felt that excluding the SCR items from the initial power core construction unfairly diminished the cost of the power core. While the Starfire and ARIES-I did not amortize the cost of the replaceable items, ARIES-II-IV chose to calculate the present worth of these items over their periods of service.

Using Present Worth for SCR Costs

Repeating: ARIES-II-IV chose to calculate the present worth of these SCR items over their periods of service.

Present Worth, $F = 1/(1-t) * [1-t * {}_{n=1}?^{T} (d_n/(1+x)^n)]$, where t is the effective tax rate = 0.3664/y, d is the fraction of the cost that is deductible in the year n, and x (nominal cost of money) = 0.1135.

For a 5-year depreciation schedule with respective depreciation values, the present worth, F, is 1.272. Thus the SCR cost is

C_{SCR} = (total direct costs FWB + divertors)*CRF*Present Worth*(1+contingency)/Lifetime

Note that this ARIES equation does not include any other replaceable items such as the heating or current drive in-vessel components or any other major replaceable items, such as gyrotrons.

GEN IV does not have a comparable cost account that considers regular replacement of significant cost items. However it is significant to observe that GEN IV EMWG has chose to disregard for the moment the complexity of present worth, tax rates, and escalation. Instead, they simply sum up all annual expenditures to the levelized cost of the borrowed capital and divide by the annual power production.

The recommendation for the Scheduled Component Replacement cost account is to include the annual replacement costs for all the significant-cost replaceable hardware components. These should not be placed in the fuel cost account. Also the cost should be reported as a simple annual expenditure with no consideration for present worth, tax status or depreciation.

Fuel Costs

This fuel cost account is quite analogous to the SCR account. Schulte identified the fusion fuel elements to be considered in the fuel account. Schulte postulated that this is a 10th of a kind plant, which would indicate that the supply and demand of tritium from other operating fusion plants would force the cost of tritium to zero market value. Purchase of deutritium would be a stable cost for a 10th of a kind reactor. The cost of tritium breeding materials, such as lithium or lithium compounds, either natural or enriched, would be included. Other costs might be neutron multipliers, cladding, other fuel materials, and annual offsite fuel processing and disposal costs.

Waganer, in the Starfire report, built on the Schulte recommendations. Tritium would be considered as a no cost fuel element as it would be continuously bred in sufficient quantities. The facilities to process the fuel constituents are a capital cost. Starfire had a quote for the cost of deuterium ($2175/kg in 1980$) and calculated needed quantities to account for usage and leakage. All other tritium breeding materials, cladding, neutron multipliers, etc., would be accounted in the SCR cost account. The annual cost of deutritium was $0.3M (1980$) or $0.76M (2008$).

Fuel Costs

As discussed earlier, Sheffield, et. al, in the Cost Assessment of a Generic Reactor, included in the Fuel Cost account the cost of first wall/blankets, limiters/divertors, some heating and current drive components, fuel, some miscellaneous replaceable component costs, and decommissioning and disposal. Sheffield took the Starfire fuel (deuterium) costs and escalated it to $0.4M. He assumed there was $30 M miscellaneous components that might be replaceable and chose to include 80% of these on an annual basis. So his subcategory of fuel cost was = (0.4 + 24*F_{cro}) M$, where F_{cro} is the related constant dollar fixed charge rate. Delene supported the Sheffield fuel algorithm.

Bathke and Miller in ARIES II-IV study returned to separating the fuel elements from the SCR hardware elements. They affirmed that there should be no cost for tritium as the breeding blanket self-breeds tritium in sufficient quantities in the long term. ARIES estimated the cost of deutritium as $3700/kg (1992$). The fuel COE for both ARIES-II and –IV was 0.03 mills/kWh or an annual cost of $0.20M (1992$) or $0.28 (2008$). ARIES-AT reported a similar fuel COE and annual cost. A higher availability would change the data but the significant digits mask any changes.

Fuel Costs

It is recommended the annual fuel costs continue to be handled per the current ARIES approach to separate the fuel and scheduled component replaceable items. It might be wise to obtain a more current update on the cost of deuterium.

The cost of the initial supply of tritium for the first fusion power plant might be a sizable one-time cost, but within a very short period of time, the plant should be tritium-self sufficient and will produce an excess tritium to start a new power plant. In the long run, the net cost of tritium should be zero and any initial costs will be balanced with sale of tritium to another power plant starting operation after ~5 years.

Decontamination and Decommissioning Costs

Schulte and Waganer (Starfire) did not identify any annual cost charge for decontamination and decommissioning and this was an oversight.

Sheffield, et al, in the Cost Assessment of a Generic Reactor did add this cost item as a separate annual cost as a 0.5 mill/kWh based on fission experience.

Delene in his update of the GENEROMAK cost model introduced the concept of LSA reduction factors for power plants with lower activation materials. These factors were applied to the decommissioning annual costs. He acknowledged that the fission disposal costs are highly speculative. At that time, a 1.0 mill/kWh was being levied on fission reactors for decommissioning. In the revised Generomak model, an LSA 4 plant would be charged 1.0 mill/kWh, an LSA of 3 would be 0.75 mill/kWh, an LSA of 2 would be 0.25 mill/kWh, and an LSA of 1 would be no charge.

The ARIES-II and IV study adopted the Delene LSA approach, but elected to charge 0.25 mill/kWh for the LSA 1 case. This practice continues into the ARIES-AT study.

It is recommended the annual decommissioning costs continue to be handled per the current ARIES approach with appropriate LSA factors until L. El-Guebaly develops a new scheme linking the decommissioning cost to the waste volume with considerations for the Class A and Class C low-level waste classification and the recycling/clearance alternate approach to geological disposal. Gen IV D&D recommendations should be reviewed for applicability, noting the differences between fission and fusion.

General Comment on Annual Costs

A general recommendation for ARIES is that all O&M, SCR, fuel, and decommissioning costs be reported in both annual costs in dollars as well as COE in mills/kWh data. This approach would allow direct comparisons without the steps of determining the power plant net electrical output and the plant capacity (or availability) factor for conversion.

It would also be prudent to advance the reported costs to a more current year for comparison purposes. It is convenient to have all ARIES reports in 1992$ but it is a bit dated.

Next Actions –yet to be done

- Continue to work with Subsystem experts and Ron Miller to create and verify the direct cost algorithms for each subsystem and major component
- Determine number of identical subsystems and major components necessary for the selected design (including EPR, subsystem demonstrations, DEMO, initial prototypes, and initial power reactors leading to the 10th of a kind power plant, including spares
- Assess the learning curve associated with the subsystem and major components

Cost Account Managers

No.	Account	CAM
20	Land and Land Rights	Waganer
21	Structures and Site Facilities	Waganer
22	Power Core Plant Equipment	
22.01	Fusion Energy Capture and Conversion	
22.01.01	First Wall and Blanket	Malang
22.01.02	Second Blanket	Malang
22.01.03	Divertor Assenbly	Raffray
22.01.04	High Temperature Shielding	El-Guebaly
22.01.05	Low Temperature Shielding	El-Guebaly
22.01.06	Penetration Shielding	El-Guebaly
22.02	Plasma Confinement	
22.02.01	Toroidal Field Coils	Bromberg
22.02.02	Poloidal Field Coils	Bromberg
22.02.03	Feedback Coils	Kessel
22.03	Plasma Formation and Sustainment	Mau
22.04	Vacuum, Plasma Core (equipment)	Najmabadi
22.05	Primary Structure and Support	Wang
22.06	Power Supplies, Switching and Energy Storage	Cadwallader
22.07	Main Heat Transfer and Transport	Raffray
22.08	Cryogenic Cooling, Magnets	Bromberg
22.09	Radioactive Materials Treatment and Management	El-Guebaly
22.10	Fuel Handling and Storage	Steiner
22.11	Maintenance Equipment	Waganer
22.12	Instrumentation and Control	Weaver
22.13	Other Plant Equipment	Waganer
23	Turbine Plant Equipment	Schultz
24	Electric Plant Equipment	Schultz
25	Miscellaneous Plant Equipment	Waganer
26	Special Materials	Waganer