Thank you for the opportunity to present this material. At the invitation of a nuclear utility, knowing of the company's fossil activities, I developed a new method of monitoring the NSSS. It solves for an absolute average flux with other BOP parameters, and then verifies results. Its verification techniques are based on 20 years of monitoring fossil-fired units. The bases of this work lies with my long wonderment as to why there is no nexus between ^1n flux and BOP. *

I understand the traditional: its impossible to know the average Φ_{AVG}, it is not required for material buckling, leakages are normalized, etc. But, I submit, Φ_{AVG} is, indeed, the driving force of why we are all in this room.

Neutronics Calorimetrics Verification

What NCV needs

What is power ?

The Inertial Process

Computation of Absolute Neutron Flux

Thermal Performance Monitoring

Summary Equations

Criticism of NCV Method

Going forward …

EXERGETIC SYSTEMS
Performance Engineering

ANS

I have 15 minutes to tell all. NCV provides a bases for improved understanding, and thus safety, of nuclear power. Among a number of performance parameters, a discrete Core Thermal Power is computed and verified … I will concentrate on concepts. Full understanding of the technology was published in a 50 page document publicly available, its reference is provided at closure. Also, this presentation is being placed on my web-site. *

What NCV Needs

is a legitimate design review by

NRC engineers

PWR plant engineer

BWR plant engineer

and plans for benchmarking,

as appropriate.

EXERGETIC SYSTEMS
Performance Engineering

ANS

I am pleading to this audience that the Neutronics Calorimetric & Verification Method be reviewed … *

What is Power ?

NRC Requires that "Core Thermal Power" (CTP) not exceed X.

CTP is defined by First Law energy balance. No nexus is established with fission power! For a typical NSSS:

3642 MW*t* (CTP, mΔh)

EXERGETIC SYSTEMS
Performance Engineering

ANS

As we know the US and other countries use Core Thermal Power to limit operations. *
This has been in-place for 50 years.

What is Power ?

NRC Requires that "Core Thermal Power" (CTP) not exceed X.

CTP is defined by First Law energy balance. No nexus is established with fission power! For a typical NSSS:

3642 MW*t* (CTP, $m\Delta h$)

1934 MW*a* (Available Exergy Flow, $m\Delta g$)

1270 MW*e* (Electrical Generation)

664 MWℓ (Irreversible Loss)

EXERGETIC SYSTEMS
Performance Engineering

ANS

As we know there are different grades of power. In older literature, folks spoke of lost work or power. Heating a space or water is classically treated as a Mega-Watt Thermal. The highest is Mega-Watt Electric. The Second Law defines an Mega-Watt Available – that is available for theoretical useful shaft output without Second Law violation. Whereas the First Law conserves mass & energy flows … an MeV release from fission is a pure exergy and is entirely available as an exergy flow (a Btu/hr). Note that both recoverable and unrecoverable exergy is "available". At the system level "available power" is destroyed given creation of only electrical power and irreversible losses … and nothing else. *

All is based on assuming fission is an inertial process.

Fission is an Inertial Process

Experimental observations indicate MeV release, after ^{1}n capture:

- **is constant (independent of incident ^{1}n exergy)**
- **has no thermodynamic reference**
- **is independent of temperature & gravity**

EXERGETIC SYSTEMS
Performance Engineering

ANS

Unique is the laboratory observation that fission release is constant: fission of 235 with a 10 MeV neutron, after accounting for KE of the system, produces the same exergy released as found from thermal fission. *
The electron volt has no thermodynamic reference, it is not affected by temperature or gravity.

Fission is an Inertial Process

Experimental observations indicate MeV release, after ^{1}n capture:

- **is constant (independent of incident ^{1}n exergy)**
- **has no thermodynamic reference**
- **is independent of temperature & gravity**
- **its <u>entire</u> release is available for power … a pure exergy**
- **for an isolated core, it is described by an exergy transform:**

$$C_E \Phi_{AVG} \Sigma_F (\vartheta_{REC} + \vartheta_{TNU}) V_{Fiss} = m_{RV} \Delta g + \sum I_{Loss}$$

EXERGETIC SYSTEMS
Performance Engineering

ANS

Fission release is pure exergy. Within the <u>core</u>, it's recoverable portion is transferred as an increase in specific exergy in the coolant, the un-recoverable portion is an irreversible lost. *

Computation of Absolute Neutron Flux

Method I: Neutron Transport Theory.

Method II: Stochastics Methods (Monte Carlo).

Method III: Traditional Neutron Diffusion Theory (profiles).

EXERGETIC SYSTEMS
Performance Engineering

ANS

We must bear in mind that all previous methods of computing flux are approximations, and have never been directly verified for the typical NSSS core. *

Computation of Absolute Neutron Flux

Method I: Neutron Transport Theory.

Method II: Stochastics Methods (Monte Carlo).

Method III: Traditional Neutron Diffusion Theory (profiles).

Method IV: NCV does not solve for flux in isolation;

EXERGETIC SYSTEMS
Performance Engineering

ANS

Proposed is NOT to compute flux in insolation. *

Computation of Absolute Neutron Flux

Method I: Neutron Transport Theory.

Method II: Stochastics Methods (Monte Carlo).

Method III: Traditional Neutron Diffusion Theory (profiles).

Method IV: NCV does not solve for flux in isolation; instead, declare the absolute Φ_{AVG} an unknown, solved in conjunction with system P_{GEN} & Q_{REJ} ... as these three are then coupled through m_{RV}.

EXERGETIC SYSTEMS
Performance Engineering

ANS

But rather, to take Φ_{AVG} and brake shaft power to the generator, and Turbine Cycle heat rejection ... all as unknowns ... coupled through Reactor Vessel coolant mass flow. Thus we have four unknowns * ... we need four equations.

Computation of Absolute Neutron Flux

Method I: Neutron Transport Theory.

Method II: Stochastics Methods (Monte Carlo).

Method III: Traditional Neutron Diffusion Theory (profiles).

Method IV: NCV does not solve for flux in isolation; instead, declare the absolute Φ_{AVG} an unknown, solved in conjunction with system P_{GEN} & Q_{REJ} ... as these three are then coupled through m_{RV}. Then verify results: compare P_{GEN} to the measured

EXERGETIC SYSTEMS
Performance Engineering

ANS

And after resolution of the unknowns, we then verify. The obvious reason electrical generation was declared an unknown was to compare the computed to the accurately measured … and then correct thru verification techniques.
*****

Thermal Performance Monitoring

$$G_{IN} \equiv Q_{FIS} + \sum P_{RV\text{-}k} + \sum P_{TC\text{-}k}$$

$$= P_{GEN} + \sum I_k$$

$$1.0 = P_{GEN}/G_{IN} + \sum I_k/G_{IN}$$

This defines a **Fission Consumption Index**:

$$1000 = FCI_{Power} + \sum FCI_{Loss\text{-}k}$$

EXERGETIC SYSTEMS
Performance Engineering

ANS

Again, the available exergy supplied to the system is the total fission release plus pump shaft power. For 20-odd years my company has monitored fossil plants using a Fuel Consumption Index. Of course, for a nuclear engine, both the fission exergy and Irreversibility terms are quite unique. For example, if the Fission Consumption Index for power decreases by 10 points, with a MSR increase from 120 to 130, with no other changes, the operator has absolute assurance that recent changes to the MSR have resulted in a 1% shift in fission rate producing shaft power to that required to overcome higher MSR losses. The NSSS has become 1% LESS effective in generating electricity. *

Summary Equations

Governing Second Law of NSSS:

$$A_1(\vartheta_{REC} + \vartheta_{TNU})\Phi_{AVG} + A_2P_{GEN} + A_3Q_{REJ} + A_4m_{RV} = L_A + A_1\psi_{LRV} \quad \text{(2ND)}$$

First Law of NSSS:

$$B_1\vartheta_{REC}\Xi(T_{Ref})\Phi_{AVG} + A_2P_{GEN} + B_3Q_{REJ} + B_4m_{RV} = L_B \quad \text{(1ST)}$$

First Law of Isolated Turbine Cycle:

$$A_2P_{GEN} + B_3Q_{REJ} + C_4m_{RV} = L_C \quad \text{(3RD)}$$

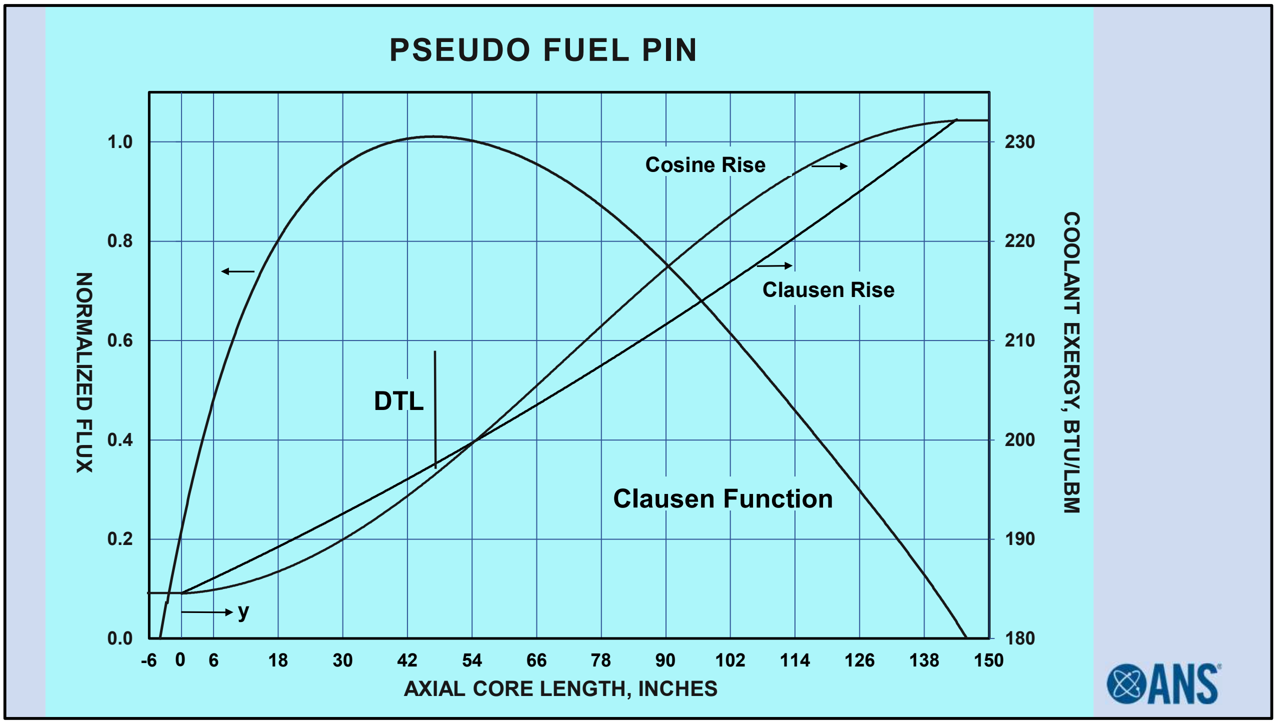
Pseudo Fuel Pin Model, Second Law of average fuel pin, Clausen asymmetric flux profile, partial integration:

$$(2D_1/B_P)(\vartheta_{REC} + \vartheta_{TNU})\Phi_{AVG} \qquad D_4m_{RV} = (2D_1/B_P)\psi_{LRV} \quad \text{(PFP)}$$

EXERGETIC SYSTEMS
Performance Engineering

ANS

These are outlines of the four equations, details are provided in the 50 page doc. Note that the fourth equation is unique – as based on an asymmetric flux profile, partially integrated in the axial. *



This is the Clausen Function of Order Two. Integration is taken to the DTL point. *

Irreversibility

$$\sum I_k = (\text{Neutrino}) + (\text{Carnot Engine Loss}) + (\text{Pump Losses}) - (\text{Sum of Component Exergy Flows})$$

$$= Q_{NEU\text{-}Loss} + \sum(1.0 - T_{Ref}/T_k)Q_{k\text{-}Loss} + \sum(P_{ii} - m_{ii}\,\Delta g_{ii})_k - \int[mdg]_k$$

EXERGETIC SYSTEMS
Performance Engineering

ANS

Computing consistent irreversibilities is an important key. The concept, of course, is nothing new, a root equation for irreversibility can be found in any chemical engineering text … except, of course, for the neutrino/antineutrino term * and the interpretation of the last term.

Irreversibility

$\sum I_k$ = (Neutrino) + (Carnot Engine Loss) + (Pump Losses)

− (Sum of Component Exergy Flows)

$$= Q_{NEU\text{-}Loss} + \sum(1.0 - T_{Ref}/T_k)Q_{k\text{-}Loss} + \sum(P_{ii} - m_{ii}\,\Delta g_{ii})_k - \int[mdg]_k$$

EXERGETIC SYSTEMS
Performance Engineering

ANS

Note that classically this term describes losses associated with heat exchangers. For example, in a common feedwater heater, a decrease of mΔg on the shell-side must be greater than an increase on the tube-side … this produces a negative total, and thus an increase in irreversible loss. * However, for a isolated fission core, all but the first term drop out.

Irreversibility

$\sum I_k$ = (Neutrino) + (Carnot Engine Loss) + (Pump Losses) − (Sum of Component Exergy Flows)

$$= Q_{NEU\text{-}Loss} + \sum(1.0 - T_{Ref}/T_k)Q_{k\text{-}Loss} + \sum(P_{ii} - m_{ii}\,\Delta g_{ii})_k - \int[mdg]_k$$

For a fission <u>core</u> (PFP Model): $\sum I_k = Q_{NEU\text{-}Loss}$

➡ Prompt Neutrino ≈ 0.68 MeV.

EXERGETIC SYSTEMS
Performance Engineering

ANS

And this equation, for a new unirradiated core, demands the loss of a prompt sub-atomic particle – without such a prompt loss, fission would violate the Second Law. The 0.68 MeV is an estimate based on CERN observations of splitting heavier isotopes. *

Irreversibility

$\sum I_k$ = (Neutrino) + (Carnot Engine Loss) + (Pump Losses) − (Sum of Component Exergy Flows)

$$= Q_{NEU\text{-}Loss} + \sum(1.0 - T_{Ref}/T_k)Q_{k\text{-}Loss} + \sum(P_{ii} - m_{ii}\,\Delta g_{ii})_k - \int[mdg]_k$$

For a fission core (PFP Model): $\sum I_k = Q_{NEU\text{-}Loss}$

➡ Prompt Neutrino ≈ 0.68 MeV.

For a fusion core: $\sum I_k = Q_{NEU\text{-}Loss} - \int[mdg]_{Core}$

➡ $\int[mdg]_{Core}$ = Equivalent exergy flow, magnetic confinement.

EXERGETIC SYSTEMS
Performance Engineering

ANS

For the fusion core, both the first and last terms have significance. Note that for a Tokamak system using a D-T reaction, the first term must include the 14.1 MeV neutron loss from the plasma – this, plus a 0.4 MeV neutrino. Further, the last term has huge importance for a Tokamak system which adds an equivalent exergy via magnetic confinement, and thus must be less than 14.5 MeV or the system will not reach sustained ignition. I am saying that inertial fusion has never properly addressed irreversible losses. In a IAEA text book on fusion, based on 2400 technical papers, there is not one reference to irreversibility. *

Criticism of NCV Method

- Nuclear fuel management needs to be integrated.
- Sensitivity to Buckling via Eq.(PFP) found to be minimal.
- Eq.(2ND) $\sum I_k$ losses dominate neutrino losses ($\vartheta_{TNU}\Phi_{AVG}$).
- First & Second Law losses need systematic organization.
- Internal MW_tD/MTU prediction needs to be addressed.
- Transient analysis needs to be addressed.

EXERGETIC SYSTEMS
Performance Engineering

ANS

Initial scoping calcs indicated that buckling would be a ideal parameter for verification purposes. However, when correctly integrating the Clausen, it was found not to be the case. The correct neutrino/antineutrino in the Governing Equation is dominated by system losses, 34% versus 4% for the antineutrino; but this is <u>not</u> the case for the PFP Model.
*****

Going Forward

On-Line Burn-Up -

Compute: $MW_tD = \Xi(T_{Ref}) \int C_E \Phi_{AVG} [\Sigma_F + \Sigma_A] \vartheta_{REC} V_{Fiss} dt$

Match ϑ_{REC} **and** $[\Sigma_F + \Sigma_A]V_{Fiss}$ **to a specific data base.**

EXERGETIC SYSTEMS
Performance Engineering

ANS

Burn-up needs to be added. Given we'll computing flux, "irradiation" becomes an issue – what is it ? Is it just fission, or fission plus absorption. … And what does MW-thermal mean regards to the actual exposure to fission power (MW-available) ?? *

Going Forward

On-Line Burn-Up -

Compute: $MW_tD = \Xi(T_{Ref}) \int C_E \Phi_{AVG} [\Sigma_F + \Sigma_A] \vartheta_{REC} V_{Fiss} dt$

Match ϑ_{REC} **and** $[\Sigma_F + \Sigma_A]V_{Fiss}$ **to a specific data base.**

Fast Transient Safety Analysis -

Eliminate fluid delays (Condenser, FW Heaters, etc.);

Transport times from RV inlet to LP turbine exhaust is seconds;

Compute Δflux & Δelectrical affects every 2 seconds.

EXERGETIC SYSTEMS
Performance Engineering

ANS

Transient analysis is viable provided the model only considers short transport times. This means the problem's boundary is reduced to the Reactor Vessel's inlet running to the LP turbine's exhaust and the generator. The electric generator should be viewed as a marvelously accurate instrument for detecting changes in neutron flux, a $d\Phi_{AVG}/d(\text{frequency})$; as based on the set of NCV equations. The objective is to create an "alarm bell" for the operator. *

Thank You

For design review participation : ***Lang@ExergeticSystems.com***

See web-site ***www.ExergeticSystems.com*** **for:**

1) A white paper on "Application of Adjustment Theory …"
(comments on DVR-based stochastics).

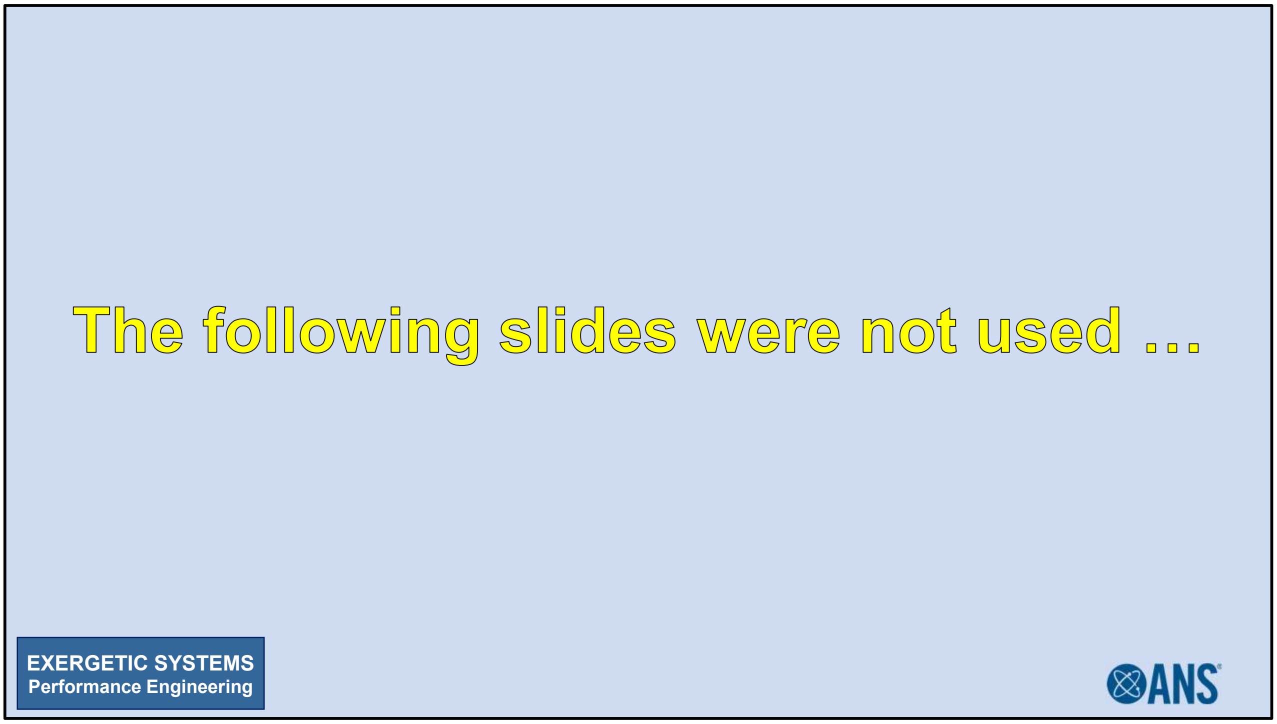
2) 50 page patent application WO/2023/049141 A9.

3) This slide presentation (plus 10 others).

EXERGETIC SYSTEMS
Performance Engineering

ANS

Thank you and please e-mail any and all comments.


The following slides were not used …
EXERGETIC SYSTEMS
Performance Engineering
ANS

Thank you.

Second Law Governing Equation

(Available Exergy) – (Generation) – (Carnot Engine Loss, Q_{REJ})

+ [SG Exergy Loss, Pump Terms, etc … $f(m_{RV})$]

= (Losses: Neutrino, Gen., Carnot, Pumps, Insulation, $\int$[mdg])

$$C_E \Phi_{AVG} \Sigma_F (\vartheta_{REC} + \vartheta_{TNU}) V_{Fiss} - P_{GEN} - (1 - T_{Ref}/T_{CNI}) Q_{REJ}$$

$$+ m_{RV} \{-\Delta g_{SVQ} + \Delta h_{RVP} + (\Delta h_{SVQ}/\Delta h_{TCI})[\Delta g_{TCI} + \Delta h_{FWP} + \sum C_P \Delta h_{CDP}]\}$$

$$= C_E \Sigma_F V_{Fiss} \psi_{LRV} + P_{GEN\text{-}Loss} + P_{FWP\text{-}Aux} + (1 - T_{Ref}/T_{RVI}) Q_{RV\text{-}Loss}$$

$$+ (1 - T_{Ref}/T_{FW}) Q_{SG\text{-}Loss} + (1 - T_{Ref}/T_{TC}) Q_{TC\text{-}Loss} - \int [mdg]_{TC}$$

$$+ (Q_{SG\text{-}Loss}/\Delta h_{TCI})[\Delta g_{TCI} + \Delta h_{FWP} + \sum C_{P\text{-}j} \Delta h_{CDP\text{-}j}]$$

This is a NSSS Second Law balance. An $m_{RV}\,\Delta g_{RVQ}$ does not appear. RV coolant flow appears only thru pump losses. *

Two First Law Equations

$$C_E \Phi_{AVG}\, \Sigma_F\, \vartheta_{REC} V_{Fiss}\, \Xi(T_{Ref}) - P_{GEN} - Q_{REJ}$$
$$+ m_{RV} \{\Delta h_{RVP} + (\Delta h_{SVQ}/\Delta h_{TCI})(\Delta h_{FWP} + \sum C_{P\text{-}j}\Delta h_{CDP\text{-}j})\}$$
$$= (Q_{SG\text{-}Loss}/\Delta h_{TCI})(\Delta h_{FWP} + \sum C_{P\text{-}j}\Delta h_{CDP\text{-}j}) + P_{FWP\text{-}Aux} + P_{GEN\text{-}Loss}$$
$$+ Q_{RV\text{-}Loss} + Q_{SG\text{-}Loss} + Q_{TC\text{-}Loss} \qquad \text{(1ST)}$$

$$- P_{GEN} - Q_{REJ} + m_{RV} (\Delta h_{SVQ}/\Delta h_{TCI})(\Delta h_{TCQ} + \Delta h_{FWP} + \sum C_{P\text{-}j}\Delta_{CDP\text{-}j})$$
$$= P_{GEN\text{-}Loss} + Q_{TC\text{-}Loss} + P_{FWP\text{-}Aux}$$
$$+ (Q_{SG\text{-}Loss}/\Delta h_{TCI})(\Delta h_{TCQ} + \Delta h_{FWP} + \sum C_{P\text{-}j}\Delta h_{CDP\text{-}j}) \qquad \text{(3RD)}$$

As much as I criticize First Law concepts, we need additional equations. We can convert the recoverable fission exergy to a $m_{RV}\,\Delta h$ (cannot reverse this conversion !!). The paper describes an Inertial Conversion Factor, $\Xi(T_{Ref})$. * We now have three equations.

Fourth Equation: PFP Model

Needed is an additional Second Law equation, carrying all its assumptions, but will not replicate Eq.(2ND) coefficients.

Developed was a Pseudo Fuel Pin (PFP) Model:

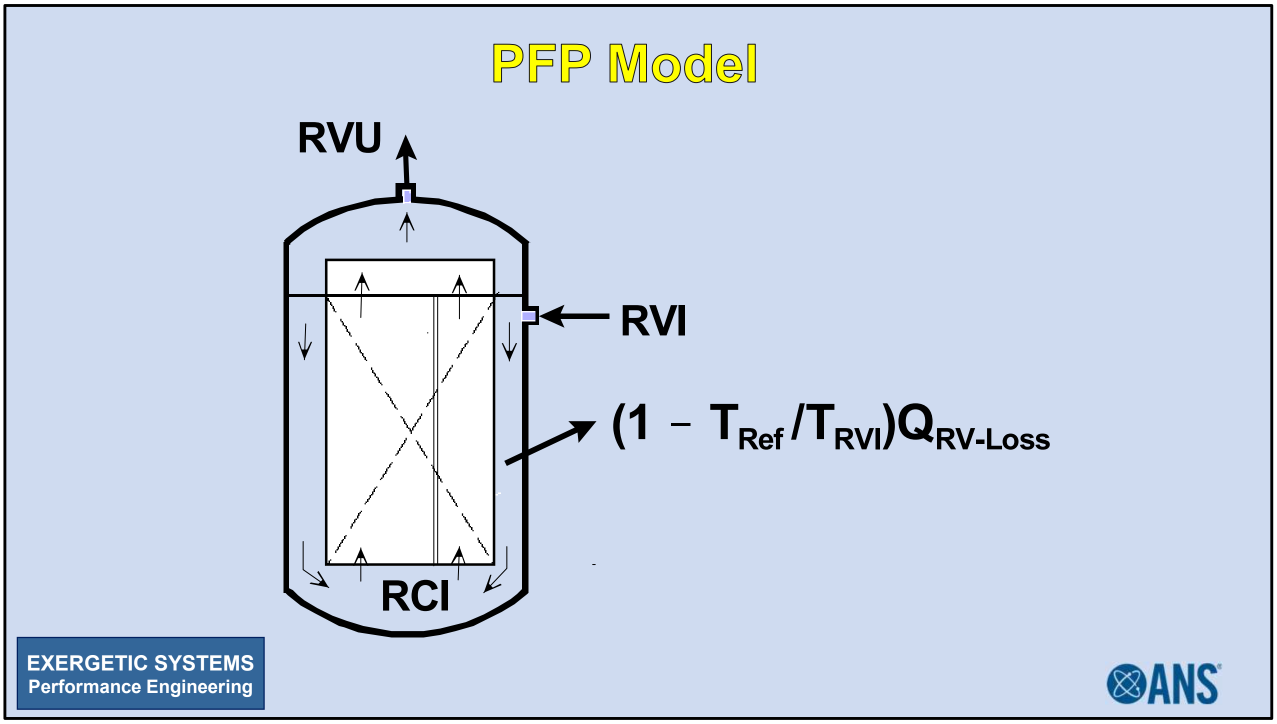
- **an average fuel pin, whose flux profile is an asymmetric trig function, producing exactly the same Φ_{AVG} as Eq.(2ND),**
- **partially integrated in the axial to max asymmetry:**

$$(2D_1/B_P)\Phi_{AVG}(\vartheta_{REC} + \vartheta_{TNU}) + D_4 m_{RV} = (2D_1/B_P)\psi_{LRV} \qquad \text{(PFP)}$$

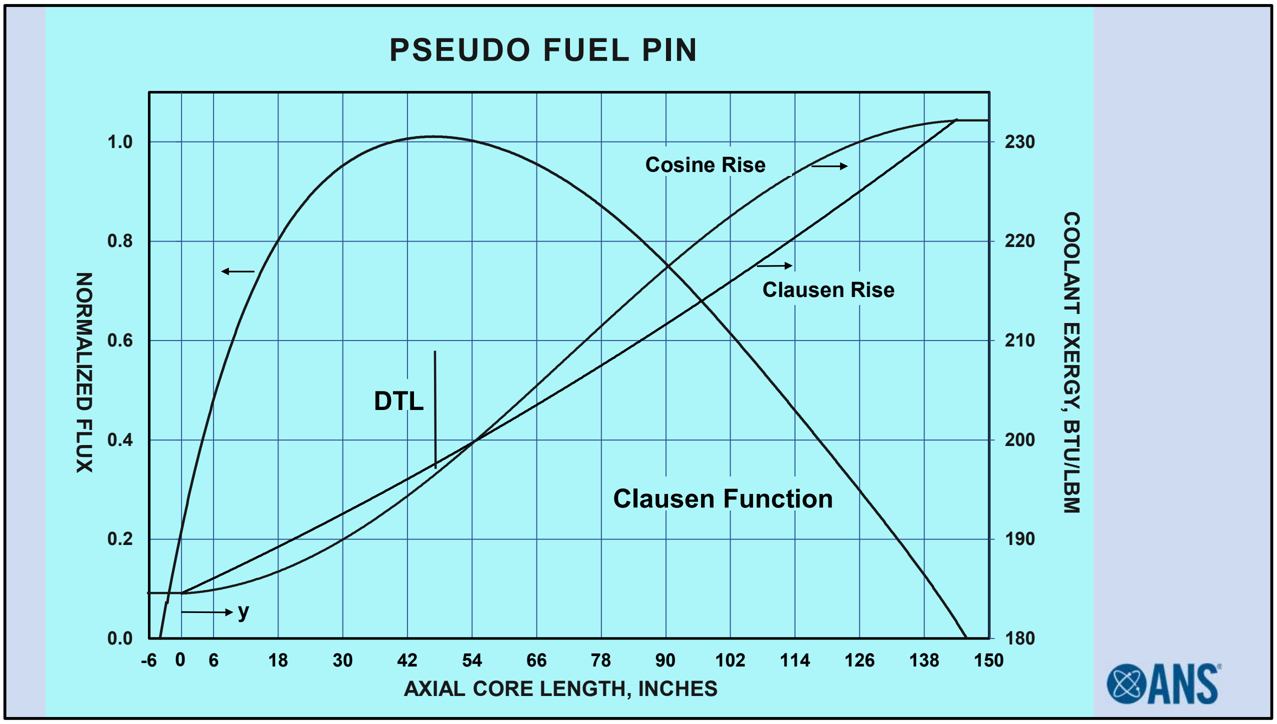
EXERGETIC SYSTEMS
Performance Engineering

ANS

A needed fourth equation is found in another Second Law application. This is the Pseudo Fuel Pin (PFP) Model. PFP key assumptions include: it represents an average fuel pin, has an asymmetric profile, and * is only partially integrated in the axial.



If we envision an average pin in the core, the only loss is the antineutrino. Vessel losses are associated with the outer annulus. * By the way, the 2.6% beta & gamma coolant heating is taken into account by the recoverable release, given assumed steady state.



The PFP is based on the Clausen Function of Order Two. Note that an assumed cosine for the PWR will yield an essentially symmetric profile. *

Proof of Process

Summary Results (Btu/hr or lbm/hr)

Parameter	Data	Data Source	Matrix Solution
Avg. Abs. Flux	1.0000×10^{13}	SAR Guess	$9.84384221 \times 10^{12}$
Gross Power	4.326742×10^{6} 1268.043 MWe	TC Kit	4.3267423×10^{6} 1268.0430 MWe
Reactor Vessel & FW Flows	138.1380×10^{6} 16.34750×10^{6}	Hand Calcs	138.1380×10^{6} 16.34751×10^{6}
Heat Rejection	8.089160×10^{9}	TC Kit	8.0891559×10^{9}

EXERGETIC SYSTEMS
Performance Engineering

ANS

These calcs were recently updated. Note the 1.6% difference in flux … an intolerable error on system efficiency. *

The Inertial Process

Total fusion release (MeV), after n_1 and n_2 collision:

- is constant (independent of incident ^{1}n exergy)
- has no thermodynamic reference
- is independent of temperature & gravity
- its <u>entire</u> release is available for power … a pure exergy
- for the core, it is described by an exergy transform:

$$C_E\, n_1 n_2 \langle \sigma v \rangle\, (\vartheta_{REC} + \vartheta_{TNU})_{Total} = m\Delta g + \sum I_{Loss}$$

EXERGETIC SYSTEMS
Performance Engineering

The same principles apply for fusion, those I_{Loss} carries huge importance for a fusion system's viability. *

Irreversibility

$\sum I_k$ = (Neutrino) + (Carnot Engine Loss) + (Pump Losses) − (Sum of Component Exergy Flows)

$$= Q_{NEU\text{-}Loss} + \sum(1.0 - T_{Ref}/T_k)Q_{k\text{-}Loss} + \sum(P_{ii} - m_{ii}\,\Delta g_{ii})_k - \int[mdg]_k$$

For a fission <u>core</u> (PFP Model): $\sum I_k = Q_{NEU\text{-}Loss}$

➡ Prompt Neutrino ≈ 0.68 MeV.

For a fusion <u>core</u>: $\sum I_k = Q_{NEU\text{-}Loss} - \int[mdg]_{Core}$

➡ $\int[mdg]_{Core}$ = Equivalent exergy flow, magnetic confinement.

EXERGETIC SYSTEMS
Performance Engineering

ANS

The principals apply to fusion. Note that for a Tokamak system using a D-T reaction, the QNEU-Loss term includes a 14.1 MeV neutron loss from the process, plus a 0.4 MeV neutrino. Further, the last term has huge importance for a Tokamak system which adds an equivalent exergy via magnetic confinement, and must be less than 14.5 MeV or the system will not reach sustained ignition given ∑I < 0.0. *

Irreversibility

$\sum I_k$ = (Neutrino) + (Carnot Engine Loss) + (Pump Losses)

− (Sum of Component Exergy Flows)

$$= Q_{NEU\text{-}Loss} + \sum(1.0 - T_{Ref}/T_k)Q_{k\text{-}Loss} + \sum(P_{ii} - m_{ii}\,\Delta g_{ii})_k - \int[mdg]_k$$

For a fission <u>core</u> (PFP Model): $\sum I_k = Q_{NEU\text{-}Loss}$

➡ Prompt Neutrino ≈ 0.68 MeV.

For a fusion <u>core</u>: $\sum I_k = Q_{NEU\text{-}Loss} - \int[mdg]_{Core} - \{\int dE_1/dt + \int dE_2/dt\}\Delta t$

➡ $\int[mdg]_{Core}$ = Equivalent exergy flow, magnetic confinement.

EXERGETIC SYSTEMS
Performance Engineering

ANS

Also, for example, if two main-sequence stars (burning with D-T reactions) collide at a high closing speed, this equation predicts NOTHING will happen – after, of course, the dissipation of KE. This is so because no non-passive process can exist with ∑I < 0.0.

Irreversibility

"The center of the galaxy [involving high closing speeds given star] collision there is much more destructive, and often the aftermath is just 'star bits' (that is, mostly hydrogen gas) spread out all over interstellar space."

Professor Sills
Department of Physics & Astronomy
McMaster University
(Astronomy, May 2020).

EXERGETIC SYSTEMS
Performance Engineering

ANS

This is proof of the sign of the $\int[mdg]_{Core}$ term.