

DETERMINATION OF THE PRICE OF RDF FOR BILLING PURPOSES

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ABSTRACT

RDF is a heterogeneous fuel whose energy value is difficult to measure. This paper presents an innovative method used by Southeastern Public Service Authority of Virginia to equate the price of RDF to: (a) the discounted cost of fuel displaced by burning RDF; and (b) the discounted revenue received for excess electrical generation by allocating the boiler output energy to steam and electrical generation.

NOMENCLATURE

Q = energy, Btu/hr (kJ/h)
 W = flow, lb/hr (kg/h)
 h = enthalpy, Btu/lb (kJ/kg)

Subscripts:

net-boiler = net energy in boiler output
net-NNSY
steam = net energy to Naval Shipyard from steam
NNSY = steam to Naval Shipyard
kW = electrical generation
S = boiler steam
B = boiler blowdown
FW = feedwater
C = condensate
MU = makeup water

kWG = electrical generation plus balance of plant losses

kW-VAP = electricity sold to VAP

Coal-kW-VAP = net boiler output from coal allocated to electricity sold to VAP

RDF = net boiler output from RDF

INTRODUCTION

The state of Virginia has authorized Southeastern Public Service Authority of Virginia (SPSA) to enter into contracts to provide for garbage and refuse collection and disposal. To provide for waste disposal SPSA has entered into a contract with the U.S. Navy to sell to the Navy a continuous and reliable supply of refuse derived fuel (RDF) produced from processible solid waste.

SPSA will own and operate a Refuse Derived Fuel Project (RDF Plant) where processible solid waste will be processed into RDF. The RDF will be conveyed to the Norfolk Naval Shipyard (NNSY) and burned at the Navy's Power Plant for production of steam and electricity. The Navy Power Plant is a cogeneration facility whose primary objective is to generate process steam to meet the needs of the NNSY and generate electricity as a byproduct. In addition, SPSA anticipates providing the Navy with additional RDF for production and sale of excess electricity to Virginia Power Company (VAP). Operating revenues for the

RDF Plant will be obtained primarily from the sale of RDF to the Navy and from the charging of tipping fees for waste disposal.

THE RDF CONTRACT

SPSA expects to realize operating revenues from the sale of RDF to the Navy under the terms and conditions of the RDF Contract. The Navy will pay SPSA for RDF under a two-tiered pricing system: Tier A and Tier B.

Because RDF is a heterogenous fuel whose energy value is difficult to measure, the price of RDF is tied to that which is measurable: steam and electrical generation. In general, Tier A pricing equates the price of RDF to the cost of coal displaced by burning RDF to produce steam and electricity not sold to VAP. Tier B pricing equates the price of the RDF to the revenue received for the generation of electricity sold to VAP.

The terms and conditions of the RDF Contract include, but are not limited to, the following:

Tier A Rate

The Navy's monthly payments for RDF not used for the generation of electricity to be sold to VAP shall be determined in accordance with the following formula which includes 85% of the cost of coal to the Navy, the boiler efficiency of the Power Plant and certain additional capital and operating expenses incurred by the Navy as a result of designing the Power Plant to co-fire both coal and RDF. The contract defines the RDF to be paid for at the Tier A rate as: RDF delivered to the Navy up to and including 0.1998×10^6 MBtu output, and all RDF in excess of 0.1998×10^6 MBtu boiler output which is not used for the generation of electricity to be sold to VAP.

$$\text{Tier A} = 0.85 \text{ CC} \times \left[\frac{Q_{\text{boiler}} - (Q_{\text{COALin}} \times n_{\text{COAL}})}{n_{\text{COAL}}} \right] - F_1 - F_2 + CA$$

where

0.85 = coal cost discount factor

CC = cost of coal, \$ per MBtu

Q_{boiler} = net boiler output MBtu expressed as the net energy gain across the boiler not used for the generation of electricity to be sold to VAP.

Q_{COALin} = boiler input from coal, MBtu

n_{coal} = boiler efficiency burning coal

F_1 = $0.65 \times$ factor for additional capital cost

F_2 = factor for additional O&M cost

CA = the cost of removal of ash, noncombustible material, and other waste generated by the Navy Power Plant

The term in the Tier A formula

$$\frac{Q_{\text{boiler}} - (Q_{\text{COALin}} \times n_{\text{COAL}})}{n_{\text{COAL}}}$$

equates to the RDF to be paid for at the Tier A rate expressed as the coal input equivalent of the boiler output energy produced by the RDF. The RDF is expressed as the coal input equivalent because it represents the coal displaced by burning RDF and can be rewritten as follows:

$$\frac{Q_{\text{RDF-Tier A}}}{n_{\text{COAL}}}$$

Substituting in the Tier A formula:

$$\text{Tier A} = 0.85 \text{ CC} \times \frac{Q_{\text{RDF-Tier A}}}{n_{\text{COAL}}} - F_1 - F_2 + CA$$

Tier B Rate

The Navy will pay for RDF received in excess of that which is required to produce 0.1998×10^6 MBtu boiler output each month which is used for the generation of electricity to be sold to VAP an amount to be determined in accordance with the following formula which takes into account 85% of the VAP payment and additional capital and operating costs incurred by the Navy as a result of designing the power plant to co-fire both coal and RDF.

$$\text{Tier B} = 0.85 \text{ VAP} - F_3 - F_4 - F_5$$

where

0.85 = VAP revenue discount factor

VAP = the monthly revenue received by the Navy for excess kWh generated by the Navy and supplied to VAP, using RDF received by the Navy in such month in excess of 0.1998×10^6 MBtu boiler output

F_3 = $0.35 \times$ factor for additional capital cost

F_4 = additional O&M cost not paid for under Tier A

F_5 = cost of coal used to generate that quantity of electricity to be paid for at the Tier B rate

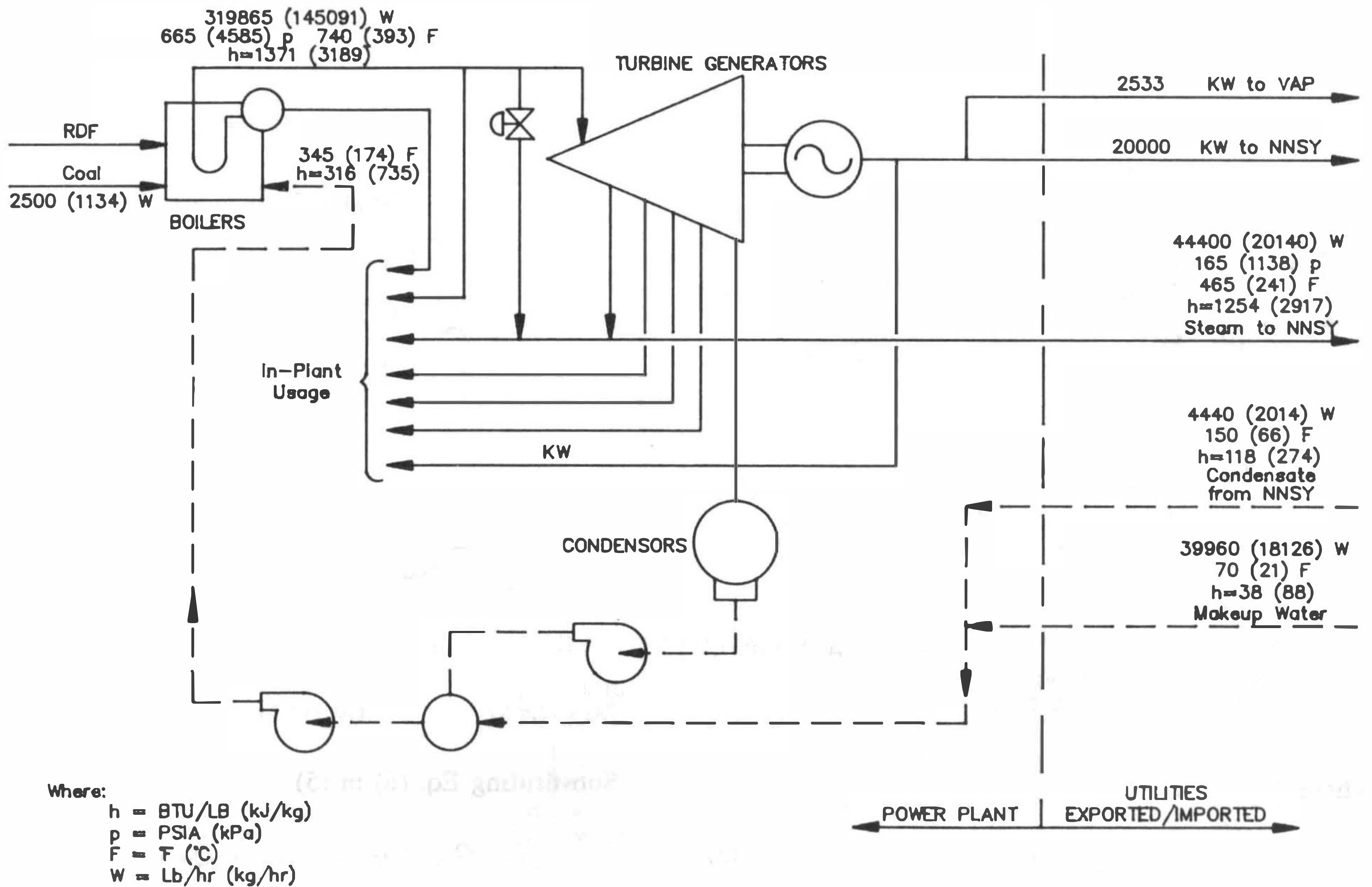


FIG. 1 NAVY POWER PLANT THERMAL CYCLE

ENERGY ALLOCATION OF BOILER OUTPUT

The boiler output energy must be allocated between coal, RDF, and that which was used to generate electricity sold to VAP (Tier B) and that which was not used for the generation of electricity sold to VAP (Tier A).

The allocation of energy between steam and electricity is not subject to a simple solution based on a few meter readings. As steam enters a steam turbine, a portion is extracted for export to the Navy and generates electricity at some variable value of efficiency, a portion is extracted for in-plant use which again generates electricity and a portion is condensed also generating electricity. Also, a portion of the steam may bypass the turbine-generator entirely for export or in-plant use. Of the electric power generated, a portion is required for in-plant use, NNSY use and the remainder is exported for sale to VAP.

Figure 1 illustrates the simplified thermal cycle of the power plant.

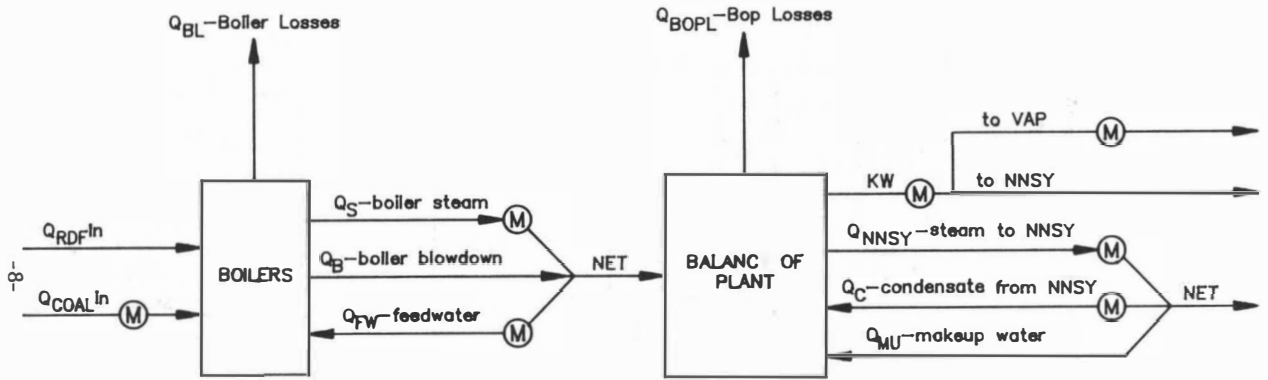
The enthalpy drop allocation method [1] was se-

lected to allocate energy between electricity and steam. This method charges process steam for only the actual energy (enthalpy) used by the process steam. This method is appropriate for determining the energy of the steam because the primary objective of the Navy power plant is to generate process steam. The energy used by electrical generation becomes the net boiler output energy minus the energy used by the process steam.

In order to determine the energy used for the generation of electricity and process steam a black box approach to the cycle was taken. Figure 2 illustrates the black box approach. By judiciously selecting the boundaries of the boxes, one need not be concerned with the complexities of the cycle within the box, only that which is entering and leaving. Equations can then be written for the energy entering and leaving these boxes.

The net energy in the boiler output is the energy gain across the boiler:

$$Q_{\text{net-boiler}} = Q_S + Q_B - Q_{FW} \quad (1)$$



Where:
 Q = Energy, BTU/HR (kJ/kg)
 KW = Electricity, KW/HR (kW/HR)
 (M) = Measured

FIG. 2 NAVY POWER PLANT ENERGY BLOCK DIAGRAM

where

$$Q = W \times h \quad (2)$$

The net energy input to the balance of plant is equal to the net energy entering from the boiler output. The energy leaving the balance of plant, including losses, is equal to the energy entering the balance of plant. Energy use within the balance of plant is reflected in the energy leaving the box. The energy balance around the balance of plant is therefore:

$$Q_{in} = Q_{out} \quad (3)$$

where

$$Q_{in} = Q_{net-boiler} \quad (4)$$

$$Q_{out} = Q_{net-NNSY-steam} + Q_{kw} + Q_{BOPL} \quad (5)$$

The majority of the balance of plant losses, Q_{BOPL} , are the heat rejected by the turbine generators to the condensers. These losses are a direct result of generating electricity and therefore are included with Q_{kw} as energy for electrical generation.

Therefore

$$Q_{WG} = Q_{kw} + Q_{BOPL} \quad (6)$$

Substituting Eq. (6) in (5)

$$Q_{out} = Q_{net-NNSY-steam} + Q_{kW} \quad (7)$$

The net energy in the process steam to the NNSY is the energy drop across the NNSY:

$$Q_{net-NNSY-steam} = Q_{NNSY} - Q_C - Q_{mu} \quad (8)$$

Substituting Eqs. (4) and (7) in (3) and solving for Q_{kW}

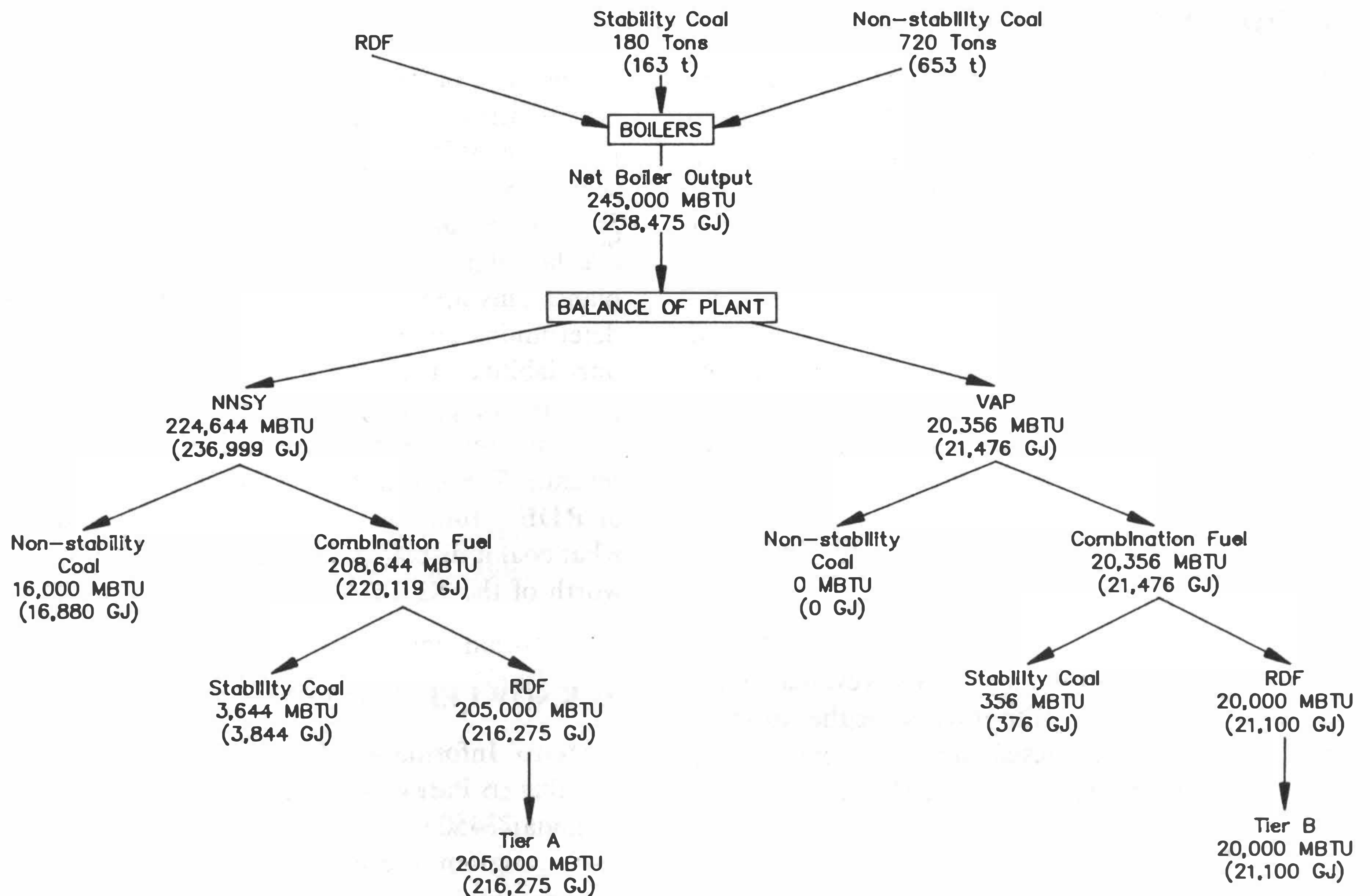
$$Q_{kW} = Q_{net-boiler} - Q_{net-NNSY-steam} \quad (9)$$

Substituting Eqs. (1) and (8) in (9)

$$Q_{kW} = (Q_S + Q_B - Q_{FW}) - (Q_{NNSY} - Q_C - Q_{mu}) \quad (10)$$

The energy value of RDF fluctuates seasonally. It also varies daily as a result of weather. The Navy may require that some coal be co-fired with RDF to ensure stable boiler operation when RDF energy values are too low. This coal is considered a necessary operating expense for RDF firing and is allocated proportionally with RDF to electricity and process steam. This coal is identified as stability coal.

It is not expected that the Navy will fire coal for the production of excess electricity for sale to VAP. The production of excess electricity should only occur



Where:
 MBTU = 10^6 BTU for One Month Period
 (GJ = 10^6 kJ for One Month Period)

FIG. 3 ENERGY ALLOCATION SUMMARY

as a result of the firing of RDF. Therefore, any coal co-fired with RDF above that which might be required to maintain stable boiler operation, is allocated first to the production of steam for the Naval Shipyard, second to electrical power for the Naval Shipyard, and finally, the remaining coal energy if any is allocated to excess electricity for sale to VAP. This coal is identified as nonstability coal, or coal which is not required for stable boiler operation when firing RDF.

Using the above equations and expanding them to account for coal and electrical power used by the Naval Shipyard, the energy equations for determining the boiler output allocated to Tier A and Tier B are as follows:

Tier B:

$$Q_{\text{RDF-Tier B}} = Q_{\text{kW-VAP}} - Q_{\text{COAL-kw-VAP}} \quad (11)$$

Tier A:

$$Q_{\text{RDF-Tier A}} = Q_{\text{RDF}} - Q_{\text{RDF-Tier B}} \quad (12)$$

For a complete derivation of these equations see the Appendix. Figure 3 illustrates the final allocation of boiler output energy to Tier A and Tier B rates.

ADDITIONAL CAPITAL COSTS

The additional capital costs are based on the difference between the estimated cost to construct the Navy Power Plant as a conventional coal-fired power plant and the estimated cost to construct the Navy Power Plant with the capability of burning RDF and coal. The factor for the additional capital cost is the additional capital costs amortized over a 30 year period. The additional capital costs include the cost of an additional turbine generator, ancillary equipment, boiler modifications, RDF storage facility, RDF fuel handling equipment and any equipment required by law or regulation to operate the Navy Power Plant burning RDF.

ADDITIONAL O&M COSTS

The additional O&M costs are the actual incremental increase in O&M expenses required of the Navy to operate and maintain the Navy Power Plant firing RDF as compared to a conventional coal-fired power plant. The additional O&M costs allocated to Tier A include those costs attributable to burning RDF. Tier A costs exclude O&M costs associated with the generation of electricity sold to VAP. The additional O&M costs allocated to Tier B are those costs not paid for under Tier A and exclude the cost of removing and disposing of ash, noncombustible material and other waste attributable to both RDF and coal paid for under Tier B.

REVENUE

The following is a summary of the revenues on a dollar per MBtu of RDF output basis for the situation given in Figure 3 and are based on a coal cost of \$2.240 per MBtu and electricity price of 3.394 cents per kWh.

TIER A

	\$ per MBtu RDF output billed under Tier A
$0.85 \times \text{coal cost} \times \frac{Q_{\text{RDF-Tier A}}}{n_{\text{COAL}}}$	2.267
$0.65 \times \text{additional capital cost factor}$	-0.493
Additional O&M cost	-0.508
Cost of ash removal	-0.008
Tier A revenue	1.274

TIER B

	\$ per MBtu RDF output billed under Tier B
$0.85 \times \text{VAP}$	2.664
$0.35 \times \text{additional capital cost factor}$	-2.759
Additional O&M costs	-0.595
Cost of coal in Tier B	-0.047
Total Tier B	-0.737
Tier B revenue	0.0
Total revenue (Tier A + Tier B)	1.161

SUMMARY

The price of RDF can be related to the boiler output energy attributable to RDF, the cost of the fuel displaced by RDF and the revenues received from the sale of excess electrical generation. The energy output from RDF can be calculated from data points which can be reliably and commonly measured in a power plant. This approach avoids the difficult problems of determining boiler efficiency when firing RDF and the unreliability of measuring the quantity of RDF supplied to the power plant.

By relating the price of RDF to coal and electrical revenue, SPSA and the U.S. Navy have made the price of RDF a function of what revenue it produces and what coal it displaces and represents the real economic worth of the RDF.

ACKNOWLEDGEMENTS

Metro Information Services, Inc. (METRO) 607 Lynnhaven Parkway, P.O. Box 8888, Virginia Beach, Virginia 23450 prepared the RDF Billing System computer program and interpreted the RDF Contract.

REFERENCES

- [1] Kallen, Howard P. "Distribution of Steam and Electrical Power Costs in an Industrial Plant." *Proceedings of the American Power Conference*, XIX (1957).
- [2] Contract N62470-80-C-39/6. "Refuse Derived Fuel Service." 19 July, 1984.

APPENDIX

NOMENCLATURE

- kW = kilowatts of electrical generation
 Q = btu/hr (kJ/h)
 n_b = boiler efficiency

Subscripts

- F = fuel
 FW = feedwater
 S = boiler steam
 BL = boiler losses
 B = boiler blowdown
 C = condensate returned from the Naval Shipyard
 MU = makeup
 BOPL = balance of plant losses

NNSY = steam to Naval Shipyard
 kW = electrical generation
 kWG = electrical generation plus balance of plant losses
 kW-NNSY = electricity used by the Naval Shipyard and in-plant use
 kW-VAP = electricity sold to Virginia Electric Power Co. (VAP)
 COALin = coal input to boiler
 RDFin = RDF input to boiler
 COAL = net boiler output from coal
 RDF = net boiler output from RDF
 SCOAL = net boiler output from stability coal
 SCOALin = stability coal input to boiler
 NCOAL = net boiler output from nonstability coal
 NCOALin = nonstability coal input to boiler
 NCOAL-
 NNSY = net boiler output from non-stability coal allocated to steam to Naval Shipyard
 NCOAL-
 kW-VAP = net boiler output from non-stability coal allocated to electricity sold to VAP
 SCOAL-
 kW-VAP = net boiler output from stability coal allocated to electricity sold to VAP
 RDF-
 kW-VAP = net boiler output from RDF allocated to electricity sold to VAP
 VAP = electrical generation to Virginia Electric and Power Co.
 GROSS = gross electrical generation

ENERGY EQUATION DERIVATIONS

$$Q_{in} = Q_{out} \quad (1)$$

Boiler

$$Q_{out} = Q_s + Q_{BL} + Q_B \quad (2)$$

$$Q_{in} = Q_{COALin} + Q_{RDFin} + Q_{FW} \quad (3)$$

where Q_s , Q_{BL} , Q_B , Q_{FW} and Q_{COALin} are measured.

Substituting equations [2] and [3] in [1] and solving for Q_{RDFin}

$$Q_{RDFin} = (Q_s + Q_B - Q_{FW}) - Q_{COALin} + Q_{BL} \quad (4)$$

$$n_B = \frac{(Q_{COALin} + Q_{RDFin}) - Q_{BL}}{Q_{COALin} + Q_{RDFin}} \quad (5)$$

where n_B is determined by test

Solving [5] for Q_{BL}

$$Q_{BL} = (Q_{COALin} + Q_{RDFin}) \times (1 - n_B) \quad (6)$$

Substituting Eq. (6) in Eq. (4) and solving for Q_{RDFin}

$$Q_{RDFin} = \frac{(Q_s + Q_B - Q_{FW}) - (Q_{COALin} \times n_B)}{n_B} \quad (7)$$

By definition

$$Q_{RDF} = Q_{RDFin} \times n_B \quad (8)$$

Substituting Eq. (8) in Eq. (7) and solving for Q_{RDF}

$$Q_{RDF} = (Q_s + Q_B - Q_{FW}) - (Q_{COALin} \times n_B) \quad (9)$$

Balance of Plant

$$Q_{in} = Q_s + Q_C + Q_{MU} + Q_B \quad (10)$$

$$Q_{out} = Q_{BOP} + Q_{NNSY} + Q_{KW} + Q_{FW} \quad (11)$$

where

Q_C , Q_{MU} and Q_{NNSY} are measured.

Substituting Eqs. (10) and (11) in Eq. (1) and solving for Q_{KW}

$$Q_{kw} = (Q_s + Q_B - Q_{FW}) - (Q_{NNSY} - Q_C - Q_{MU}) - Q_{BOPL} \quad (12)$$

The majority of the balance of plant losses, Q_{BOPL} , are the heat rejected by the turbine generators to the condensers. These losses are a direct result of generating electricity and therefore are included with Q_{kw} as energy used for electrical generation.

$$Q_{kWG} = Q_{kw} + Q_{BOPL} \quad (13)$$

Substituting Eq. (13) in Eq. (12) and solving for Q_{kWG}

$$Q_{kWG} = (Q_s + Q_b - Q_{FW}) - (Q_{NNSY} - Q_c - Q_{MU}) \quad (14)$$

kW Allocation

kW sold to VAP.

$$Q_{kW.VAP} = \frac{kW_{VAP} \times Q_{kWG}}{kW_{GROSS}} \quad (15)$$

where kW_{VAP} and kW_{GROSS} are measured

$$Q_{kW.NNSY} = Q_{kWG} - Q_{kW.VAP} \quad (16)$$

Coal Energy Allocation

By definition

$$\frac{Q_{COAL}}{Q_{SCOAL}} = \frac{n_B \times Q_{COALin}}{n_B \times Q_{SCOALin}} \quad (17)$$

where Q_{COALin} and $Q_{SCOALin}$ are measured.
Nonstability coal:

$$Q_{NCOAL} = Q_{COAL} - Q_{SCOAL} \quad (18)$$

Nonstability coal allocated to steam to NNSY:

$$\text{If } Q_{NCOAL} \leq Q_{NNSY} \quad (19)$$

$$\text{Then } Q_{NCOAL.NNSY} = Q_{NCOAL}$$

$$\text{Otherwise } Q_{NCOAL.NNSY} = Q_{NNSY}$$

Nonstability coal to VAP:

$$Q_{NCOAL.kw.VAP} = Q_{NCOAL} - Q_{NCOAL.NNSY} \quad (20)$$

Stability Coal:

Stability coal allocated to VAP:

$$\frac{Q_{SCOAL.kw.VAP}}{Q_{SCOAL.kw.VAP} + Q_{RDF.kw.VAP}} = \frac{Q_{SCOAL}}{Q_{SCOAL} + Q_{RDF}} \quad (21)$$

$$Q_{SCOAL.kw.VAP} = \frac{Q_{SCOAL} \times (Q_{SCOAL.kw.VAP} + Q_{RDF.kw.VAP})}{Q_{SCOAL} + Q_{RDF}} \quad (22)$$

$$Q_{kW.VAP} = Q_{RDF.kw.VAP} + Q_{SCOAL.kw.VAP} + Q_{NCOAL.kw.VAP} \quad (23)$$

Rearranging (23):

$$\begin{aligned} Q_{SCOAL.kw.VAP} + Q_{RDF.kw.VAP} \\ = Q_{kW.VAP} - Q_{NCOAL.kw.VAP} \end{aligned} \quad (24)$$

Substituting Eq. (24) in Eq. (22):

$$\begin{aligned} Q_{SCOAL.kw.VAP} \\ = \frac{Q_{SCOAL} \times (Q_{kW.VAP} - Q_{NCOAL.kw.VAP})}{Q_{SCOAL} + Q_{RDF}} \end{aligned} \quad (25)$$

Stability coal allocated to NNSY and in-plant use:

$$Q_{SCOAL.NNSY} = Q_{SCOAL} - Q_{SCOAL.kw.VAP} \quad (26)$$

Coal allocated to VAP:

$$Q_{COAL.kw.VAP} = Q_{NCOAL.kw.VAP} + Q_{SCOAL.kw.VAP} \quad (27)$$

RDF Energy Allocation

Tier B:

By definition

$$Q_{RDF.Tier B} = Q_{RDF.kw.VAP} \quad (28)$$

$$Q_{RDF.kw.VAP} = Q_{kW.VAP} - Q_{COAL.kw.VAP} \quad (29)$$

Tier A:

By definition

$$Q_{RDF.Tier A} = Q_{RDF} - Q_{RDF.Tier B} \quad (30)$$

where all terms in Eqs. (29) and (30) have been defined above.