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# ADAPTATION OF THE BOILER AS CALORIMETER METHOD TO TWO-STAGE MUNICIPAL WASTE COMBUSTORS

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## ABSTRACT

The Boiler As Calorimeter (BAC) method was adapted for use with two-stage municipal waste combustors. For this purpose, a special thermodynamic input-output model was developed, together with a related work methodology. The latter draws on the guidelines set forth in the ASME Test Codes, but was supplemented by improvised field procedures. The Hartford County Resource Recovery Facility (HCRRF) with a processing capacity of 360 tons per day served as the test bed.

Extensive calculations were carried out for five different BAC test periods spread over a period of several years. To some extent, data shortages were overcome by coupling the records of the plant computer with the results of annual emission testing. Other supplemental data sources included front loader calibrations and ash analyses.

In addition to the higher heating value (HHV), the system thermal efficiencies and the specific steaming rates were calculated. Insofar as possible, they were correlated to each other. All were presented in consistent tabular format and augmented with diagrams. Several key parameters, such as losses from radiation and unburnt carbon, exceeded expectations. On the other hand, the designer's efficiency goals were not met. Potential causes for these shortcomings were identified and discussed.

Historical trend analysis indicated a declining HHV as determined by the BAC test work. In this context, the hypothesis is advanced that mandatory materials recycling may have had a negative effect. In support of this hypothesis, the results of computer modeling and an actual waste sort are taken into consideration.

Scores of recommendations are made about how to facilitate future BAC analyses in facilities equipped with two-stage combustors. They run the gamut from improved accuracy to reduced work effort. In addition, a method for better burn-out is proposed which could lead to increased thermal efficiency.

## INTRODUCTION

The Boiler As Calorimeter (BAC) method to determine boiler efficiency has received much attention in prior ASME publications. Its purpose is to determine the higher heating value (HHV) of waste fired when it is not possible to collect a representative sample.

Usually, application of the BAC method has been limited to large municipal waste combustors (MWC's) which are equipped with articulated grates and waterwall boilers. This raises the question: Can the BAC method be adapted for use in small MWC's which feature two-stage combustion in multiple-hearths? Is this possible even though small MWC's tend to have less sophisticated in-plant instrumentation?

In order to find the answer, the Harford County Resource Recovery Facility (HCRRF) was selected for an in-depth investigation. It has four two-stage MWC's for an installed facility capacity of 360 short tons per day (STPD). These MWC's have been in operation since January 1988. More descriptive details may be found in another publication [1]. The facility was financed through the Northeast Maryland Waste Disposal Authority (NEM) and is operated by a private company, i.e. Waste Energy Partners as part of a Service Agreement [2].

The plant instrumentation has a mix of sensors which monitor some operating parameters on an individual combustor basis and others on a facility basis. All are connected to the plant computer which can receive and store operating data at predetermined intervals. For the BAC work, the computer was asked to print out ten or more complete plant status reports (PSR's) for a given analysis period. A typical PSR is provided in Table 1. Typically, others were printed out at about 20 minute intervals. While the PSR's yielded many of the BAC parameters needed, they did not cover the three most critical flow rates: (1) fuel, (2) ash and (3) flue gas. Field procedures were devised to overcome these problems. One of these involved combining the annual emission test with collection of the PSR's. Others were special scale determinations of fuel and ash.

## CREATION OF THERMODYNAMIC INPUT-OUTPUT MODEL

Classical input-output-loss models have been developed by the ASME Performance Test Code Committee for "Large Incinerators" and for "Steam Generating Units" [3][4]. These models are not readily applicable to mass burning, waterwall-type incinerators. Presently, another Performance Test Code Committee on "Waste Combustors with Energy Recovery" is developing a test code using the boiler as a calorimeter which will be known as PTC34. Modular, two-stage incinerators however have several features which are different enough to warrant special consideration. Consequently, a new model (presented in Figure 1) was tailor-made.

This model allows for primary combustion air to go to the lower chamber and for separate secondary combustion air to go to the upper chamber. In addition, fans are incorporated which serve to recirculate flue gas through the boilers. Other refinements address the various water sprays which increase evaporation. These include dust suppression sprays into the loaders, cooling sprays into the lower chambers and ash sprays into the ash sumps. The quench tanks were also included, since they are subject to heat and mass losses.

Of course, it is necessary to draw a boundary around the system and to label the many items which cross it either as inputs (arrow pointing inward) or as outputs (arrows pointing outward). In order to calculate thermal credits and losses, it is necessary to designate a reference temperature to which all calculations are to be referenced. As a matter of convenience, 80°F was selected as the constant temperature for this purpose.

For the BAC analysis, the HCRRF combustion and energy recovery calculation system was simplified by substituting a single larger furnace for the four smaller ones. The three boilers were combined into a single equivalent boiler. Thus, a more generic system evolved.

In the early part of project development, the suggestion was made that ASME-type performance testing be done as part of acceptance testing. This suggestion was not accepted however, thus preventing validation of the input-output model with real information from actual plant operations. Instead, there are only the BAC tests with their affiliated derivations in this paper which are offered as a substitute.

## WORK METHODOLOGY

As a first step, all available test data was reviewed for completeness and concurrency. At the end of the review, a decision was made as to which days and hourly periods were to be included. At a minimum, three consecutive days and three test periods were selected. Total elapsed time ranged from 10 to 24 hours. (Note: The Acceptance Test was an exception; it lasted 121 hours.)

Obviously, because of the complexity and variability of the test parameters involved, higher totals of elapsed time are preferred. This would yield more data points or larger samples for better averaging. In practice, compromises had to be made which may be the inevitable consequences of activities characterized as "low budget" and "multiple objectives". Also, there were some inadequacies in scheduling and coordination.

The basic idea was to work up representative averages for the various parameters needed for the BAC analysis. For nearly equal periods, arithmetic averages were considered adequate. However, for uneven periods, time-weighted averages were calculated. In the end, five BAC test periods were selected.

Another problem concerned the fact that a variety of test contractors were used over the years by the operator; they all reported in different formats. Often, there was no agreement on reference conditions and summaries were presented in lieu of actual test data sheets. Another gaping hole was left in the information base by the unwillingness of both the operator and the contractors to keep a detailed test log. Only such a log will enable an analyst who was not a participant to make correct interpretations or judgments long after the fact.

There is yet another condition which is responsible - at least in part - for the difficulties encountered. This condition is an almost classical conflict between the engineering and business aspects of a project. Engineers are trained problem solvers and they measure the success of a project by one or more efficiency tests. The business people negotiate compromises and settle for less. In the case of the HCRRF, the draft technical specification did include efficiency tests [5]. Most notable of these was the ASME Performance Test Code 33.

During negotiations, this requirement was deleted and replaced with a minimum steam generation guarantee. Thus, the Service Agreement which is the tripartite relationship binding the Company, the Authority and the County together does not require any efficiency tests, either upon acceptance or over the life of the facility [2]. Moreover, no limit was placed on the amount of unburnt combustibles permitted in ash. This weakened the Agreement. This is significant, because unlike waterwall incinerators, two-stage combustors (with the first stage operating in the "starved air" mode) are particularly prone to poor burn-out. Consequently, the item called "unburnt carbon loss" takes on special significance. In fact, it may cause a big swing in the results. However, all of this does not detract from the fact that the BAC analysis is a promising efficiency test.

A basic work flow schedule was developed which was applied to all BAC test periods. It is depicted in Figure 2. Because of the difference between waterwall incinerators and two-stage combustors, several extra steps were added in order to sufficiently customize the standard BAC analysis which is being developed by the ASME. The schedule consists of the following tasks which were performed sequentially. Several may require reiterations depending on the quality of the data on hand:

I. <u>Analyses of Gas, Steam and Water</u>
- Ia. Control Room Data
- Ib. Non-Control Room Data
- Ic. Stack Data
- Id. Environmental Data

II. <u>Analyses of Fuel and Air</u>
- IIa. Water from Hydrogen in Fuel
- IIb. Nitrogen from Fuel
- IIc. Nitrogen Balance to Determine Total Air
- IId. Moisture from Combustion Air
- IIe. Moisture from Ash Tank and Ash Spray
- IIf. Moisture from Spray in Charge Boxes
- IIg. Moisture Spray in Lower Chambers
- IIh. Water Balance

III. <u>Heat Recovery</u>
- IIIa. Net Heat Recovered in Primary Steam
- IIIb. Net Heat to Blowdown
- IIIc. Net Heat to Cooling System

IV. <u>Heat Loss Calculations</u>
- IVa. Heat Loss Due to Dry Flue Gas
- IVb. Heat Loss Due to Sensible and Latent Heat in Flue Gas Moisture
- IVc. Heat Loss Due to Radiation and Convection
- IVd. Heat Loss Due to Unburnt Carbon or Combustibles in Residue
- IVe. Heat Loss Due to Sensible Heat in Dry Residue
- IVf. Heat Loss Due to Sensible Heat in Residue Moisture
- IVg. Heat Loss Due to Sensible Heat in Quench Water Overflow

V. <u>Heat Credits</u>
- Va. Sensible Heat in Dry Combustion Air
- Vb. Sensible Heat in Combustion Air Moisture
- Vc. Sensible Heat in Fuel
- Vd. Sensible Heat from Furnace

and Boiler Fans
(1) Primary Combustion Air Fans
(2) Secondary Combustion Air Fans
(3) Flue Gas Recirculation Fans

Ve. Sensible Heat in Evaporated Water

Vf. Sensible Heat in Quench Overflow

VI. Determination of HHV

VIa. Summation of Outputs
VIb. Summation of Losses
VIc. Summation of Credits
VId. Addition of Unaccounted for Losses

VII. Determination of Overall System Efficiency

VIIa. Divide Net Heat in Primary Steam by HHV
VIIb. Multiply by 100%

Several of the tasks enumerated above were actually divided into sub tasks. For example, IIe included the following sub tasks:

(1) Estimate average solids concentration in wet ash based on sample analyses. Multiply by wet ash total from scale records in order to determine the dry weight of ash removed by the ash conveyors.

(2) Derive average sump temperature by utilizing lower chamber temperatures recorded in PSR's and correcting them with calibration data obtained from manual temperature testing previously done directly in ash sumps.

(3) Calculate the specific heat of dry ash following Section 7 in ASME-PTC33, working with compositional analyses of either present or past ash samples.

(4) Determine average quench tank temperature either from present or past manual thermometry.

(5) Calculate the amount of sensible heat delivered from dry ash to the quench tank by multiplying the product of ash dry weight and specific heat with the temperature difference between sump and quench tank.

(6) With the aid of the Steam Tables, calculate enthalpy difference between water vapor at atmospheric pressure and liquid at quench tank temperature.

(7) Divide sensible heat delivery by enthalpy difference in order to obtain estimate of the amount water evaporated from quench tank into lower chamber.

Typically, about thirty pages of calculations and research notes were needed to carry out all tasks for each BAC period, i.e. a rather large volume of effort. To the extent possible, the procedures outlined in the ASME Test Codes most notably PTC33 were adhered to. Where necessary, supplemental procedures were improvised. However, within the confines of this paper, it is not possible to describe even one complete set in detail, although several problem areas are highlighted in subsequent sections of this paper.

## SELECTION OF TEST PERIODS

Ideally speaking, each BAC test period should be comprised of simultaneous determinations of the amounts of MSW fired and ash generated, ash quality, stack gas parameters and plant operating parameters. There should be at least three separate sequential test runs performed on separate days. The purpose of this arrangement is to buffer out the many variations which result from the firing of a non-specification type of fuel such as MSW.

In practice, both the test engineer and the data analyst must settle for less because of inevitable cost and schedule limitations. After having diligently collected and evaluated all available test data, it became clear that the HCRRF was not any different. An additional complication was the fact that much of the testing was done without any prior consideration of BAC requirements. Thus, the study effort more closely resembled the search for a solution to a jigsaw puzzle than for the execution of a planned engineering program.

Was it a hopeless undertaking? Not necessarily. Although largely fragmented, a large amount of information was accumulated which could possibly be organized in a manner which ultimately would yield useful results. Towards this end, certain selection criteria were defined as being desirable, including the following:

- A minimum acceptable test duration of 24 hours
- The requirement of at least three

separate test days
- Weight data on MSW firing
- Weight data on ash generation
- Ash quality data from lab testing
- At least three determinations of stack parameters from APC testing
- Plant status reporting at a fre quency of twice per hour, or better
- Consistency in test procedures and data formats

In accordance with these criteria, all available information was evaluated. Amongst the criteria, the availability of concurrent ash test data was judged absolutely essential. Three periods were then identified for which either all or most of these criteria were met, i.e. January 1988, August 1992 and June 1993. The first period was the facility's original acceptance test while the other two were part of subsequent annual emission tests. The three periods so selected were called "Primary Test Periods" in Table 2.

After selection of the primary test periods, two other test periods remained for which no original ash test data could be found. The two periods occurred during annual emission testing in September 1990 and August 1991. Therefore, they were called "Secondary Test Periods" in Table 2. It was hoped that by first performing the BAC analysis for the primary periods, enough experience would be gained for estimating data missing from the secondary periods.

The lack of direct MSW and ash test data was a particular handicap and, as a consequence, assumptions and data substitutions had to be made. A summary of operating parameters for the five test periods is furnished in Table 3.

## FUEL DETERMINATIONS

In the absence of a pit and crane system, it is difficult to properly track the fuel rate (FR) in the HCRRF. Essentially, there are four possible avenues to choose from:

- Weigh scale records
- Steamproduction records
- Front loader calibrations
- Flue gas measurements

Assuming that regular calibration schedules are maintained by the operator, the amount of waste received for processing in the HCRRF is accurately known. If necessary, trucks are weighed twice, i.e. once upon arrival (when they are full) and once upon departure (when they are empty). The difference in truck weights represents the amount left for processing. (Besides regular MSW, waste tires are also delivered and weighed.) Any items which are rejected by the company as being "unacceptable waste" are collected and weighed before removal to the landfill. Thus, by subtracting the amounts rejected from the amounts delivered, the net amount of waste processed by the HCRRF through incineration is established for extended periods of time.

Normally, the incineration part of the HCRRF operates 7 days a week, 24 hours per day, but waste deliveries are limited to 51/2 days a week. Also, waste deliveries fluctuate from "heavy" to "light" days. As a consequence, the operator must build up and maintain a stock pile on the tipping floor at all times. While not impossible, it does occur on rare occasions that operations start on a given day with an empty tipping floor (or segment thereof) and finishes 24 hours later with an empty tipping floor (or segment thereof). Most of the time, the regular weigh scale records are of little use to BAC testing in the HCRRF. They are only meaningful for keeping monthly and annual records, because any short-term events tend to average out over longer periods of time.

Front loader calibrations are an improvised substitute method with questionable accuracy. Typically, on the morning of a given test day one of the front loaders is designated as the "incinerator feeder". With its fuel tank presumed to be half-full and an operator of average weight at the controls, the front loader is weighed empty. The front loader is then returned to the tipping floor and its bucket is filled with waste. During this maneuver, the front loader operator must exercise his judgment twice. First, he must acquire what seems to be normal or representative waste. Second, he must do his best to fill the bucket to the proper level.

Afterwards, the front loader with its bucket full is returned to the scale pad for a second weighing. From there, the operator returns the FL to the tipping floor where he will answer the next call coming up at one of the incinerator load annunciator panels. He will then dump the entire contents of the bucket into the associated charge box. The latter will then go through its pre-programmed operation while reporting electronically to the plant computer the identity of the particular incinerator involved, together with the occurrence of one load cycle. This is replicated for each load.

By subtracting the full weight from the empty weight, the net weight charged to the incinerator is obtained on a "per bucket" basis. The apparent bulk density (BD) of the waste charged is then calculated simply by dividing the known bucket volume into the net weight. Historically, the BD values vary within the 7.5 to 12.0 lb/ft$^3$ range.

As testing progresses throughout the day (or at least until the day shift ends), the plant computer records and totals the number of load cycles for each of the four incinerators. This information forms part of the PSR's and is readily available in printouts. The average fuel rate (FR) is then derived by simple arithmetic. For any given time period, the load cycles for all four incinerators are totaled out and divided by the length of the time period. The result is the average number of load cycles per hour (LC/h) on a facility basis. (Note: There is one common stack for all four incinerators which mandates calculations on a facility basis.)

The next step is to multiply the average LC/h by the BD and divide by the volume of the particular bucket used. The end result is the average fuel rate in [lb/h], or if divided further by 2,000 lb/st in short tons per hour [stph]. During all of this, it is assumed that the initial BD determination was representative indeed and that the FL operator's judgment was consistent throughout the day or the test period. The method can be improved a little by scheduling another calibration for the afternoon. In that case, the average of two calibrations rather than a single one can be used.

How accurate is this whole approach? Not very. In search of an alternative, we have made numerous attempts to find any simple and dependable correlations between the gas parameters and the FR, but none was found, at least not the easy way. Throughout most 8 to 10 hour test periods, many of the gas parameters seem to vary too much, regardless of whether or not the data sources are PSR's or annual emission test reports.

Nowadays, some may prefer the steam flow rate in lieu of the FR as the reference parameter. Obviously, the steam flow rate is another key parameter in the BAC methodology as well. In the HCRRF, there are at least two independent sources of steam flow information. The first source is individual steam flow meters which are connected to each of the three boiler outlets. Their outputs can be added in order to get the facility production rate. The second source is a separate flow meter which works directly off the common high pressure manifold. The first source and the second are often not entirely in agreement, which forces selection of one as the more appropriate one for the BAC analysis. In the absence of concurrent calibration data, such selection becomes a judgement call.

How does one derive the fuel rate based on steam monitoring? One approximate method involves calculation and application of the monthly specific steaming rate, or SSR in [lb of steam/lb waste]. Typically, the SSR is derived once a month, based on total gross steam production and total net waste incinerated. In the past, the monthly average SSR ranged from 2.25 to 3.25 during the course of a year. Lower values were customarily experienced in the summer months if waste tires were not co-fired. By taking total steam production for any given BAC test period and dividing it by the appropriate monthly SSR, an average FR for the test period can be estimated.

In MSW as a boiler fuel, the concentrations of hydrogen and to a smaller extent nitrogen are of interest because both serve as inputs to the BAC analysis. The hydrogen concentration is needed for calculating the amount of water which is chemically formed during combustion. As will be discussed later, chemical water is the largest single component in the water balance. This is a unique feature of MWC's. From the water balance, free water in fuel is then derived by difference.

Although numerically rather small, the nitrogen concentration is still needed for completing the nitrogen balance as specified in the existing ASME Test Codes. The basic premise is that the total amount of nitrogen (determined as $N_2$ through ORSAT analysis of the stack gas) has two sources: combustion air and fuel. Regrettably, neither source was experimentally determined at the HCRRF. Yet, the nitrogen balance is a vital step towards calculating the total amount of air fed into the combustion process.

By taking samples and subjecting them to a series of chemical tests called ultimate analysis, both hydrogen and nitrogen can be determined in their elemental concentrations. While the chemical tests are standard fare for fuel laboratories, procedures for collecting and processing "representative" samples from MSW are often a controversial matter.

Another approach involves a waste sort coupled with a selective lab workup. This means that during a given day, the entire waste stream is physically pulled apart in the field and sorted into major component piles. These piles are weighed in order to establish the fractional composition of MSW. Then samples are taken from each pile and brought to a fuel lab for proximate and ultimate analyses. Afterwards, composite proximate and ultimate analyses are calculated by simply adding up the component values which have first been multiplied by their respective fractions.

In any case, both experimental approaches are laborious, inaccurate and expensive. At the time when our BAC study got underway, no ultimate analyses based on the actual testing of waste deliveries to the HCRRF were available to us. Therefore, a substitute method had to be found. Files were searched for published data which would list the elemental constituents (from ultimate analysis) together with the composite HHV's (from bomb calorimetry). Also, it was suggested that the concentrations of hydrogen and nitrogen would vary in some common fashion relative to the HHV.

But for simplicity, the notion of variability was dropped in favor of working with averages. Towards this end, the supposition was made that, in the end, the HHV as determined through BAC analysis will fall into the 4,500 to 5,000 Btu/lb as fired (AF) window. Accordingly, all H and N test values for HHV's reported in the literature within this window were culled for the calculation of arithmetic averages. The results were HHV=4,809 Btu/AF-lb, H=3.83% and N=0.62% and they were entered as such into the calculating process.

## ANALYTICAL RESULTS OF PRIMARY TESTS

In Table 4a, the January 1988 period seems to stand out in a class by itself. More net heat was recovered in primary steam than during any subsequent test period. (See Item IIIa.) The grand total for the HHV came to 5,346 Btu/lb-AF which is rather high. Is this possible? The answer is probably yes.

Most importantly, waste tires were added to regular MSW at an average rate of 7.40% by weight of total fuel fired. Depending on what HHV one wants to assign to the rubber and/or tire component, the overall HHV for the mix is bound to be high. Other favorable circumstances may include the following:

(a) The plant was new and the heat transfer surfaces were relatively clean. Much of the equipment was in peak condition, which improved heat recovery efficiency.

(b) The amount of MSW and tires fired were carefully weighed and recorded on a load-by-load basis. Thus, there was less uncertainty over the fuel rate, which is the common denominator of many of the calculations.

(c) The weather was exceptionally cold. This means that the combustion air (which gets drawn across the tipping floor) was very low in moisture content. As a result, less airborne moisture needed to be superheated during combustion. Because there was less flue gas moisture, less sensible heat was lost with it through the stack. (See Item IVb.)

(d) The test was scheduled shortly after the New Year holiday. According to eye witnesses, many discarded Christmas trees were spotted in the waste pile. Such trees are dry and high in volatiles. Consequently, their presence must have been a Btu booster.

(e) There was no apparent diversion

of high Btu materials due to recycling.

Generally, Item IVc (Radiation & Convection Losses) appeared higher than what conventional wisdom would seem to dictate. None of the data available to us from the literature was developed specifically for two-stage combustors. Compared to the more compact waterwall boilers, there are more combustor and boiler components and they are spread further apart. A detailed side investigation was performed in order to assess radiation and convection losses on a component-by-component basis.

From design drawings, the surface area of each component such as the combustion chambers, hot gas ducts, boilers and economizers were calculated. The individual surface temperatures were estimated and verified in some instances with portable thermometers. Thereafter, the approximate coefficients of combined heat transfer from radiation and convection were picked from Figure 4 in PTC33 [3]. Heat loss calculations followed Section 5.2.1.1.3 in PTC33. The resultant totals ranged from about 170 to 220 Btu/lb-AF, or 3.8 to 4.3% of total HHV. By comparison, the ABMA chart in Fig. 8 of PTC4.1 would suggest only about 1%, or less [4].

Item IVd, i.e. Unburnt Carbon in Residues, is another troublesome subject. Again, it appears to be a larger loss than the one associated with waterwall boilers firing the same type of fuel as reported elsewhere. Even though the two-stage combustors have more retention time, they lack the continuous fuel bed agitation which articulated grates provide in waterwall boilers. Consequently, bulky items are less crushed and generally there is poor mixing of the ash. Furthermore, the degree of burn-out appears to vary widely in two-stage combustors. The lack of homogeneity and the random presence of oversized particles makes proper ash sampling and analysis difficult. Therefore, it is not always done and, even if it is done, the results may be questionable. Nevertheless, during August 1992 such testing was actually done and the unburnt carbon loss was found to be exceedingly high.

One potential remedy was previously suggested in the form of "burn-out-beams" in the tail section of the lower chambers [6]. The principle involved would call for the mounting of a single hollow beam above the ash bed in transverse fashion. The beam contains a series of small orifices which, when charged with compressed air, would cause air jets to strike the ash bed. In testing elsewhere, it was demonstrated that light unburnt particles, especially paper and plastics, can attain flotation. The beam's height and angle of rotation are adjustable in order to aim the jets in a manner which allows the particles to return to the lower chambers' thermal reaction zone. The amount of compressed air is expected to be small enough so that some sort of a starved-air environment is retained in the lower chamber.

Items IVe, f and g are difficult to pin down in the absence of instrumentation which would yield all of the measurements needed for setting up mass and thermal balances for the ash system. These and related issues were thoroughly investigated in separate ash studies [7][8].

Heat credits are influenced by the choice of a system reference temperature and how the thermodynamic boundaries are drawn up. In the HCRRF, there are no air preheaters to enable direct preheating of the combustion air. Instead, only a modest amount of indirect preheating is achieved by drawing ambient air first over the outside walls of the combustion chambers before it enters the combustion air fans. Due to the cold ambient conditions during January 1988, there were several heat deficiencies which are marked with negative signs.

With regard to unaccounted-for losses, the general practice is to assign a value of 0.5-1%. Given the level of detail to which our analyses were performed, we felt that 0.5% was appropriate. With 5,346 Btu/lb-AF, the HHV for tire cofiring during January 1988 was about 3% higher than the 5,200 Btu/lb-AF used by the designer. The HHV's for plain MSW during August 1992 and June 1993 with 4,591 and 4,493 Btu/lb-AF are remarkably close to the 4,500 Btu/lb-AF used by the designer.

## ANALYTICAL RESULTS OF SECONDARY TESTS

The analysis of secondary test periods conformed to the same patterns previously established for the primary test periods. The main difference lies in the fact that no concurrent ash test data were available. Therefore, additional assumptions and estimates had to be made. This affected Items IVd through IVg in Table 4b. For example, it was assumed that the results of unburnt carbon testing conducted several weeks in advance could still be applied to the September 1990 BAC test period, even though they appeared to be excessively high.

The unburnt carbon problem not withstanding, the results for the September 1990 period do not seem to fit in with those for the other four BAC test periods. While normally the net heat recovered in primary steam accounts for 51 to 63% of total HHV, in September 1990 only 44% was recovered. Furthermore, with 53%, the subtotal for heat losses exceeded the more regular 37 to 46%. Why did these excesses occur? Could it be that there was something unusual in the MSW, or was the facility operated poorly?

Since the grand totals for the HHV's in 1990 and 1991 were found to be nearly identical, we tend to discount the first reason. On the other hand, the second is bolstered by the fact that with a load factor or LFg=115%, the combustors were apparently overloaded. The LFg is mass based and it is obtained by dividing the amount of fuel actually burned by the design capacity. Since such overloading reduces retention time of the average MSW particle in the lower chamber, one may deduce that excessive unburnt carbon is one of the adverse consequences.

## DETERMINATION OF SYSTEM EFFICIENCY AND ITS CORRELATION TO HHV AND SSR

The purpose of the thermal management system in the HCRRF is to capture a maximum amount of the heat liberated through combustion of MSW in the form of steam. Accordingly the system thermal efficiency can be defined as

$$\eta_t = \text{(Net Heat in Primary Steam [Btu in steam per lb fuel - AF])} / \text{(HHV[Btu per lb of fuel - AF])} \times 100\%$$

This formula was applied to results previously obtained for the various BAC test periods in order to calculate the corresponding system efficiencies. The latter are displayed in Table 5 and a range of 44 to 59% is indicated. The maximum in January 1988 seems to be related again to favorable conditions which were previously cited: (a) The plant was new, (b) the HHV was high and (c) the heat release rate was at a maximum. Likewise, the minimum in September 1990 may have been related to overloading, as previously mentioned. On the other hand, the improvement to 56% in June 1993 may be due to boiler improvements made during the prior year. These included cutting additional manways into the boilers for more complete and frequent cleaning. Besides, refinements in feedwater management resulted in reduced blowdown losses.

The specific steaming rate, or SSR is a measure of how much steam, on average, is generated for each pound of MSW fired. It is defined as follows:

$$SSR = \text{(Gross Steam Produced During Test Period in [lb])} / \text{(Amount of MSW in [ST] Fired During Test Period x 2000), [lb/ST]}$$

For each BAC test period, the actual SSR's were calculated and they are listed in Table 5. Similar to the $\eta_t$ above, the SSR varies widely with the absolute high when tires were cofired in the new plant in 1988. This is followed by the absolute low in 1990 when the plant was overloaded. A new but lesser high in 1993 is attributed to boiler improvements. It is also possible to link the SSR with the $\eta_t$ and the HHV by setting up the following formula:

$$SSR = \frac{\eta_t \text{ x HHV}}{100\text{x } \Delta h} \quad \text{with } \Delta h = h_g - h_f$$

The enthalpy of steam leaving the boiler, i.e. $h_g$, is assumed to be for dry and saturated steam at average header pressure as indicated in the PSR's. (Note: In reality, the quality of this steam may only be 99.5% and it could be slightly superheated.) The enthalpy of the feedwater entering the boiler, i.e. $\Delta h_f$, is evaluated at the average feedwater supply temperature which is derived from the PSR's. The enthalpy difference h is the same item which was previously called "net heat in primary steam". The BAC test results are shown in Table 5.

If both, the $\eta_t$ and the $\Delta h$ were constants, then the SSR would simply become a function of the HHV. One could then test for one and calculate the other. This would be particularly convenient on a monthly basis because the operator already reports monthly totals for steam and fuel. Thus, the SSR can be calculated and a statement made regarding the HHV without going through the PSR's and the BAC procedure.

Unfortunately, neither the $\eta_t$ nor the $\Delta h$ are constants, although only the first varies appreciably. Could there exist a hidden inter relationship between them? In an attempt to find out, the curve shown in Figure 3 was developed using the BAC test data. When tires are not cofired, the $\eta_t$ appears to vary linearly with the SSR, i.e. the increase of one causes a commensurate increase of the other. Once tires are added in significant amounts, the curve tends to level off. In none of the cases were the values originally proposed by the design engineer reached. Moreover, the slopes of the design curve and the test curve appear to be different.

In order to facilitate comparisons, the BAC test dates were also entered on the curve. The two extreme points, i.e. 1988 and 1990 can be explained by referring to extensive cofiring of tires in 1988 and severe overloading in 1990. Although more test values would help to prove it, >52% and <57% appears to be the window for the normal load regime. $\eta_t = 53.5\%$ might be a good average to work with.

The remaining issue concerns the enthalpy difference $\Delta h$. Does it vary, too? If so, by how much? In Table 5, the values are given for the five BAC test periods. The results fall fairly close together, with deviations of only $\pm 1$ % above or below the arithmetic average of $\Delta h = 997$ Btu/lb. By substituting averages of $\eta_t$ and $\Delta h$ into the above formula, the rather simple relationship $SSR = 0.537 \times 10^{-3}$ HHV is found. It can be applied with reasonably good results to BAC 1991, 1992 and 1993, which exclude the extreme points of BAC 1988 and 1990.

## HISTORICAL TRENDS AND MATERIALS RECYCLING

Is there a general movement of BAC parameters in the course of time? In Figure 4, the HHV and $\eta_t$ values are plotted for five years. During the last four years, two trends emerged, although both exhibit a rather modest slope. The HHV declined while the $h_t$ improved. While the $\eta_t$ can possibly be explained by upgraded technical operations as previously discussed, the HHV may be related to adverse changes in fuel composition. The likelihood of the latter was suspected to be the consequence of mandatory materials recycling which was implemented in 1992.

In order to find out, a separate study was conducted which drew on computer programs available from the following sources:

- Gershman, Brickner & Bratton (GBB) Study of Harford County Waste Sort
- Anne Arundel Sorting Experience
- MSW Model from Franklin Associates
- Ogden Martin Systems Lotus
- NEM Model for Harford County

A great many assumptions went into the making of these models, but their full discussion is not possible within the context of this paper. However, in Figure 5, several functions are graphed which attempt to correlate the HHV to the recycling percentage. The Franklin, NEM and Seattle functions show several common characteristics:

(1) The origins at 0% recycling indicate an average HHV nearly equal to 5000 Btu/lb. (Franklin and Seattle only.)

(2) As the recycling increases from 0 to about 10%, there is a rise in the HHV. As recycling is further increased, the HHV reaches a plateau.

(3) After recycling reaches about 30%, the HHV declines sharply.

The HHV's, as determined by the BAC method for MSW processed in the HCRRF, do not seem to agree with any of these. The most obvious reasons include the fact that for the exclusive firing of MSW, the HHV never did exceed 4,600 Btu/lb by much. This was true when recycling did not exist or it was in its infancy. Furthermore, the HHV (as determined by BAC) actually decreased during the last years when curbside separation and recycling got underway in Harford County. Therefore, it became necessary to develop a new model which would more closely resemble the facts. This was called the Beaumont Environmental Inc. (BEI) model and its curve was added to Figure 5. Its details are discussed in another report [9].

Although accurate recycling rates were difficult to come by, there are two estimates. For the 1991/92 period, a recycling rate of 3.4% was estimated by the NEM. For 1993, about 20.0% was reported by the NEM. The corresponding HHV's as determined by BAC analysis were then entered in Figure 5. Their location indicates close conformance to the model developed by BEI and there is reason to believe that this is not by coincidence. Additional testing and analysis would be required to further prove that a true causal relationship is involved.

## CONCLUSIONS AND RECOMMENDATIONS

(1) Segregation of the BAC periods into primary and secondary test periods was an unfortunate complication. The primary periods were useful in validating basic understanding and execution of the BAC methodology. The primary results were then applied successfully to making the estimates which were needed to fill in data gaps in the secondary periods. It would have been much simpler to deal only with primary periods, but because of missing data, this was not possible. Yet, the primary periods alone would not have been enough for discussing potential historical trends.

(2) While the BAC procedure as described above may appear extreme and laborious, it certainly should serve as the guide for future testing. One can then negotiate on the particulars.

(3) Although more would have been desirable, the data delivered was sufficient for getting the BAC analysis started. For the better part, the instrumentation worked well. However, there were some discrepancies which were difficult to resolve. There appears to be ample room for improvement. Calibration checks should be performed immediately before the BAC periods. In some cases, sensors need to be changed. In other cases, additional sensors need to be installed. Consequently, an instrumentation improvement program is advisable. For example, the existing HP vent meter should be replaced with a vortex type, which is more accurate across the entire scale. In addition, a new vortex type of flow meter should be installed in the HP steam line which supplies the feedwater pump turbine drive. This would eliminate another important source of guesswork. In any case, the PSR's can and should be improved. Also, the determinations of fuel and ash generation can and should be improved. The same applies to testing the quality of ash. Regular BAC testing may also become the basis for settling potential disputes in the future. This could happen if the quality of fuel moves outside the limits expected when the Service Agreement was first framed.

(4) Performance of the CEM system could be enhanced by adding an $O_2$ sensor and improving the reliability of the existing moisture and flow rate sensors. Regular instrumentation checks and recalibrations need to be scheduled as appropriate. Conduct a check-out test before starting each BAC test period. Conceivably, an upgraded CEM could eliminate the need to supplement the PSR's with data from concurrent annual emission testing.

(5) A concerted effort needs to be made to identify and quantify major inbound air leaks. Likewise, concerns over high amounts of excess air need to be cleared up because excess air means a loss of energy. The operator should be encouraged to invest in a portable combustion analyzer in order to track down this problem.

(6) Together with the HHV, the BAC method permitted the concurrent determination of the system efficiency and the specific steaming rate. Several useful correlations were developed which may pave the way for monthly BAC reporting in the future.

(7) While the operator may continue to make some improvements in equipment and operations, these are bound to be of relatively minor significance. However, installation of the proposed

burn-out beams could make a major difference because about 7% to 20% (of system efficiency) is lost due to unburned combustibles leaving with the ash [6]. Such losses create a snowball effect which is evidenced by increased ash production.

(8) Nothing is as important as the consistent delivery of good fuel to the HCRRF. If the BAC results are correct and applicable, then there is a historical downward trend in the HHV which is not good. During BAC '93, the HHV dropped below the design value of 4,500 Btu/lb for the first time. If this trend persists, there may be trouble ahead with the steam conversion guarantees unless thermal efficiency can be raised by further positive changes in technical operations.

(9) There appear to be indications that curbside materials recycling has hurt technical operations in the HCRRF. Although some recycling may be beneficial (like the removal of glass and metal), the disadvantages seem to have outnumbered the advantages. The chief question is now whether or not the HHV, the SSR and the SAR will level off at their present levels. Continued BAC testing along the lines discussed in this report can provide the answer.

(10) It is suggested that a BAC analysis be performed at least once a year following the integrated test methodology, i.e. simultaneous BAC, APC and ash testing. The discontinued practice of monitoring make-up water by reading the service water clock should be resumed. This would help to perfect steam and water balances for the analysis.

(11) Consider applying a short-cut version of the BAC method to the monthly reports which the operator prepares for the NEM. This would allow closer monitoring of the success of technical operations. Trouble areas could then be better identified for discussions between the NEM, the County and the Company. Monthly seasonal profiles together with annual trend lines could be established in order to differentiate short-term deviations from long-term effects. Annual BAC testing would then serve to verify the monthly BAC procedures.

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[3] ANSI/ASME "Performance Test Code 33-1978: An American Standard for Large Incinerators", The American Society of Mechanical Engineers, New York, NY, 1978.

[4] ANSI/ASME "Power Test Code 4.1-1979: Steam Generating Units", The American Society of Mechanical Engineers, New York, NY, 1979 (Reaffirmed).

[5] "Basis of Negotiation (BON) Document for the Procurement of the Harford County Resource Recovery Facility", Volume One, Northeast Maryland Waste Disposal Authority, Baltimore, MD, July 1984.

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[7] "An Investigation into the Properties of Ash from the Harford County Resource Recovery Facility", 92TR-035, Beaumont Environmental Inc., Wheatley Heights, NY, November 30, 1992 (Unpublished).*

[8] "HCRRF Ash Test II", Technical Report 93TR-043, Beaumont Environmental Inc., Wheatley Heights, NY, August 30, 1990 (Unpublished).*

[9] "HHV Determination by Application of BAC Method to Two-Stage MSW Combustors", 93TR-045, Beaumont Environmental Inc., Wheatley Heights, NY, January 27, 1995 (Unpublished).*


*May be obtained from the author upon request.

TABLE 1 EXAMPLE OF HCRRF PLANT STATUS REPORT

DATE: 08-06-92 TIME: 1539

INCINERATORS:

| | | |
|---|---|---|
| 1997 | Deg F | Unit #1 Upper Chamber Temperature |
| 1221 | Deg F | Unit #1 Lower Chamber Temperature |
| 000.0 | In $H_2O$ | Unit #1 Upper Chamber Air Supply |
| 007.4 | In $H_2O$ | Unit #1 Lower Chamber Air Supply |
| 1753 | Loads | Unit #1 Loads Charged Into Incinerator |
| 0153 | Deg F | Unit #1 Cooling Water Inlet Temperature |
| 0071 | GPM | Unit #1 Cooling Water Inlet Flow |
| 0177 | Deg F | Unit #1 Cooling Water Outlet Temperature |
| 0035 | PSIG | Unit #1 Cooling Water Outlet Pressure |
| 2087 | Deg F | Unit #2 Upper Chamber Temperature |
| 1488 | Deg F | Unit #2 Lower Chamber Temperature |
| 001.0 | In $H_2O$ | Unit #2 Upper Chamber Air Supply |
| 005.9 | In $H_2O$ | Unit #2 Lower Chamber Air Supply |
| 7007 | Loads | Unit #2 Loads Charged Into Incinerator |
| 0153 | Deg F | Unit #2 Cooling Water Inlet Temperature |
| 0000 | GPM | Unit #2 Cooling Water Inlet Flow |
| 0191 | Deg F | Unit #2 Cooling Water Outlet Temperature |
| 0035 | PSIG | Unit #2 Cooling Water Outlet Pressure |
| 2131 | Deg F | Unit #3 Upper Chamber Temperature |
| 1760 | Deg F | Unit #3 Lower Chamber Temperature |
| 000.0 | In $H_2O$ | Unit #3 Upper Chamber Air Supply |
| 000.0 | In $H_2O$ | Unit #3 Lower Chamber Air Supply |
| 0055 | Loads | Unit #3 Loads Charged Into Incinerator |
| 0153 | Deg F | Unit #3 Cooling Water Inlet Temperature |
| 0079 | GPM | Unit #3 Cooling Water Inlet Flow |
| 0190 | Deg F | Unit #3 Cooling Water Outlet Temperature |
| 0034 | PSIG | Unit #3 Cooling Water Outlet Pressure |
| 2079 | Deg F | Unit #4 Upper Chamber Temperature |
| 1265 | Deg F | Unit #4 Lower Chamber Temperature |
| 000.0 | In $H_2O$ | Unit #4 Upper Chamber Air Supply |
| 007.3 | In $H_2O$ | Unit #4 Lower Chamber Air Supply |
| 1688 | Loads | Unit #4 Loads Charged Into Incinerator |
| 0154 | Deg F | Unit #4 Cooling Water Inlet Temperature |
| 0071 | GPM | Unit #4 Cooling Water Inlet Flow |
| 0180 | Deg F | Unit #4 Cooling Water Outlet Temperature |
| 0036 | PSIG | Unit #4 Cooling Water Outlet Pressure |

BOILERS:

| | | |
|---|---|---|
| 1718 | Deg F | Boiler #1 Inlet Temperature |
| 0370 | Deg F | Boiler #1 Outlet Temperature |
| 0.578 | In $H_2O$ | Boiler #1 Duct Pressure |
| 00.74 | In $H_2O$ | Boiler #1 Differential Pressure |
| 0369 | Deg F | Boiler #1 Feedwater Inlet Temperature |
| 016.0 | Inches | Boiler #1 Steam Drum Level (8" Normal Level) |
| 0360 | Minutes | Boiler #1 Soot Blower Interval Preset |
| 1543 | Deg F | Boiler #2 Inlet Temperature |
| 0263 | Deg F | Boiler #2 Outlet Temperature |
| 0.544 | In $H_2O$ | Boiler #2 Duct Pressure |
| 00.48 | In $H_2O$ | Boiler #2 Differential Pressure |
| 0364 | Deg F | Boiler #2 Feedwater Inlet Temperature |
| 007.4 | Inches | Boiler #2 Steam Drum Level (8" Normal Level) |
| 0360 | Minutes | Boiler #2 Soot Blower Interval Preset |
| 1622 | Deg F | Boiler #3 Inlet Temperature |
| 0375 | Deg F | Boiler #3 Outlet Temperature |
| 0.408 | In $H_2O$ | Boiler #3 Duct Pressure |
| 00.28 | In $H_2O$ | Boiler #3 Differential Pressure |
| 0379 | Deg F | Boiler #3 Feedwater Inlet Temperature |
| 008.0 | Inches | Boiler #3 Steam Drum Level (8" Normal Level) |
| 0360 | Minutes | Boiler #3 Soot Blower Interval Preset |

BOILER FEEDWATER:

| | | |
|---|---|---|
| 0121 | Deg F | CBD Heat Exchanger Inlet Temperature |
| 0122 | Deg F | CBD Heat Exchanger Outlet Temperature |
| 0152 | Deg F | Plate and Frame Outlet Temperature |
| 0000 | Deg F | Feedwater Pump Discharge Temperature |

COOLING SKID:

| | | |
|---|---|---|
| 0099 | PSIG | Cooling Pump Discharge Pressure |
| 0343 | GPM | Cooling Pump Discharge Flow |
| 0154 | Deg F | Cooling Pump Discharge Temperature |
| 0099 | PSIG | Booster Pump Discharge Pressure |
| 0001 | GPM | Booster Pump Discharge Flow |

COOLING SYSTEM:

| | | |
|---|---|---|
| 0175 | Deg F | Plate and Frame Inlet Temperature (Cooling Water Side) |
| 0159 | Deg F | Plate and Frame Outlet Temperature (Cooling Water Side) |
| 0162 | Deg F | Isolation Gate #1 Outlet Temperature |
| 0158 | Deg F | Isolation Gate #2 Outlet Temperature |
| 0160 | Deg F | Isolation Gate #3 Outlet Temperature |
| 0158 | Deg F | Isolation Gate #4 Outlet Temperature |
| 0159 | Deg F | Isolation Gate #5 Outlet Temperature |
| 0159 | Deg F | Isolation Gate #6 Outlet Temperature |
| 0159 | Deg F | Isolation Gate #7 Outlet Temperature |
| 0157 | Deg F | Isolation Gate #8 Outlet Temperature |
| 0160 | Deg F | Isolation Gate #9 Outlet Temperature |

ID FAN SYSTEM:

| | | |
|---|---|---|
| 0319 | Deg F | #1 ID Fan Inlet Temperature |
| 0333 | Deg F | #2 ID Fan Inlet Temperature |
| 0.460 | In $H_2O$ | System Draft |

STACK MONITORING:

| | | | | | |
|---|---|---|---|---|---|
| 0334 | Deg F | Temperature | 0147 | PPM | NO |
| 0055 | SCFM | Velocity | 0046 | PPM | $SO_2$ |
| 0000 | Percent | Opacity | 0007 | Percent | $CO_2$ |
| 0000 | PPM | CO | 0016 | Percent | $H_2O$ |

FACILITY STEAM AND CONDENSATE:

| | | |
|---|---|---|
| 1860 | PPHx10 | Boiler #1 Steam Flow |
| 0311 | PSIG | Boiler #1 Steam Pressure |
| 2590 | PPHx10 | Boiler #2 Steam Flow |
| 0360 | PSIG | Boiler #2 Steam Pressure |
| 1930 | PPHx10 | Boiler #3 Steam Flow |
| 0368 | PSIG | Boiler #3 Steam Pressure |
| 2180 | PPHx10 | Total Steam Flow |
| 0344 | PSIG | Turbine Inlet Steam Pressure |
| 0000 | PPHx100 | Total Steam Flow |
| 0349 | PSIG | Total Steam Pressure |
| 0000 | GPM | Total Condensate Return Flow |
| 0220 | Deg F | Total Condensate Return Temp. |
| 0140 | GPM | Total Feedwater Supply Flow |
| 0238 | Deg F | Total Feedwater Supply Temp. |

REMOTE STEAM AND CONDENSATE:

| | | |
|---|---|---|
| 0000 | PPHx10 | Building #5126 Steam Flow |
| 0000 | PSIG | Building #5126 Steam Pressure |
| 0000 | PPHx10 | Building #3312 Steam Flow |
| 0000 | PSIG | Building #3312 Steam Pressure |
| 0000 | GPM | Building #5126 Condensate Flow |
| 0000 | Deg F | Building #5126 Condensate Temp. |
| 0000 | GPM | Building #3312 Condensate Flow |
| 0000 | Deg F | Building #3312 Condensate Temp. |

STEAM AND CONDENSATE TOTALS:

| | | |
|---|---|---|
| 55472596 | Lbs x 10 | Boiler #1 Steam Total |
| 55737431 | Lbs x 10 | Boiler #2 Steam Total |
| 52053161 | Lbs x 10 | Boiler #3 Steam Total |
| 13487263 | Lbs x 10 | Turbine Inlet Steam Total |
| 06869955 | Lbs x 100 | Total Steam Total |
| 77259415 | Gal x 10 | Total Condensate Return Total |
| 22106289 | Gal x 10 | Total Feedwater Supply total |
| 49839248 | Lbs x 10 | Building #5126 Steam |
| 81108450 | Lbs x 10 | Building #3312 Steam Total |
| 00006754 | Gal | Building #5126 Condensate Total |
| 00634943 | Gal | Building #3312 Condensate Total |

TABLE 2 CRITERIA FOR SELECTING BAC TEST PERIODS AT THE HCRRF

| Test Month & Year | Stack Tests xRuns =Days | Weight Info. | | Test Duration Hours | Notes |
|---|---|---|---|---|---|
| | | MSW | Ash | | |
| Primary Tests: | | | | | |
| Jan. '88 | 2x3=6 | Orig. Wt. Data | Orig. Wt. Data | (5x24)+0.55 = 120.55 | No peripheral data taken. Correlation w/ash testing but incomplete ash quality determinations and tires were cofired. |
| Aug. '92 | 3x1=3 | Orig. Wt. Data | Orig. Wt. Data | 8 + 8 + 8 = 24.00 | Peripheral plant data taken. Correlation w/ash testing. Ash quality determination. |
| June '93 | 3x1=3 | FL Calibr. | Monthly Subst. | 10.75+5.67+8.00=24.42 | Not all test data are for completely concurrent test periods, 3 separate days. No peripheral data measurements (temperature & humidity of combustion air). Ash quality determinations. Correlation w/ash testing. |
| Secondary Tests: | | | | | |
| Sep. '90 | 3x1=3 | FL Calibr. | Monthly Subst. | 3.65+3.22+3.70=10.57 | MSW data is dubious. No actual ash data, monthly avg. as substitute. No peripheral data taken. No correlation w/ash testing. Test duration rather short, i.e. less than half of the criterion. |
| Aug. '91 | 3x1=3 | FL Calibr. | Monthly Subst. | 13.62+14.97+11.22=39.80 | MSW data is dubious. No actual ash data taken, monthly avg. used as substitute. No periphal data taken. No correlation w/ash testing. |

TABLE 3 HCRRF-COMPARATIVE SUMMARY OF OPERATING PARAMETERS DURING TEST PERIODS[1]

| Test Periods | 1-05/10-88[2] | 9-26/28-90 | 8-27/29-91 | 8-04/06-92 | 6-08/10-93 |
|---|---|---|---|---|---|
| Test Parameters | | | | | |
| COMBUSTORS | | | | | |
| UC Temp, °F | 1,912 | 1,947 | 1,989 | 2,024 | 1,978 |
| LC Temp, °F | 1,294 | 1,608 | 1,569 | 1,534 | 1,303 |
| Lds Chgd #/h | 30.56 | 26.83 | 29.56 | 29.79 | 29.44 |
| FR, st/h[3] | 14.45 | 17.17 | 15.32 | 12.79 | 14.45 |
| SAR[8], lb/lb | 0.4200 | 0.4154 | 0.3505 | 0.4114 | 0.4489 |
| BOILERS | | | | | |
| Gas Inlet °F | 1,576 | 1,552 | 1,531 | 1,583 | 1,616 |
| Gas Outlt °F | 368 | 428 | 383 | 329 | 428 |
| FW Inlet °F | | | | | |
| Econo/Boiler | | 232/368 | 255/382 | 242/370 | 235/370 |
| 241/389 | | | | | |
| Steam Prod | | | | | |
| psig | 348 | 362 | 370 | 346 | 352 |
| lb/h | 85,011[4] | 68,863 | 73,883 | 60,242[4] | 73,702 |
| SSR lb/lb | 3.109 | 2.056 | 2.411 | 2.355 | 2.550 |
| P "WC | 2.067 | 2.153 | 0.357 | 0.450 | 0.181 |
| Blowdown %[5] | 12.22 | 10.39 | 15.99 | 8.71 | 8.26 |
| FANS | | | | | |
| Pressures | | | | | |
| LC "WC | 8.72 | 4.93 | 5.20 | 6.20 | 7.19 |
| UC/ID "WC/"WC | | 3.63/0.376 | 3.93/0.453 | 3.93/0.446 | 0.10/0.495 |
| NA/0.470 | | | | | |
| STACK | | | | | |
| $N_2$[6]% vol dry | 78.81 | 80.13 | 80.25 | 80.28 | 80.63 |
| $CO_2$[6]% vol dry | 7.120 | 8.100 | 7.867 | 7.273 | 7.485 |
| $O_2$[6]% vol dry | 14.070 | 11.767 | 11.883 | 12.450 | 11.885 |
| EA[6] % | 209 | 125 | 127 | 142 | 127 |
| Moist, vol [6] % | 9.95 | 13.80 | 15.13 | 15.28 | 10.84 |
| ACFM[6] | 88,410 | 87,349 | 83,733 | 63,599 | 80,376 |
| ACFx$10^3$ ÷ st | 367.1 | 305.2 | 327.9 | 298.4 | 333.7 |
| DSCFM[6] | 53,908 | 47,515 | 47,531 | 36,497 | 46,866 |
| DSCFx$10^3$ ÷ st | | 223.9 | 166.0 | 186.2 | 171.2 |
| 194.6 | | | | | |
| Stack Temp°F | 325 | 394 | 346 | 316 | 346 |
| Outside Air Temp°F[6][7] | 19.6 | 65.0 | 83.5 | 79.2 | 79.9 |

Notes:
(1) General Source: Plant Status Reports and supplemented by Operator Log.
(2) Includes 7.4% tires by weight.
(3) "st" denotes short tons.
(4) Totalizer reading.
(5) Weight percent of feedwater flow.
(6) Values taken from stack test reports.
(7) Average air temperatures measured by National Weather Service at the Baltimore-Washington International Airport Actual temperatures at HCRRF location may vary.
(8) Specific Ash Rate

TABLE 4a HCRRF-RESULTS OF BAC ANALYSES[1] - PRIMARY TEST PERIODS

| Test Period | January 1988[2] | | August 1992 | | June 1993 | |
|---|---|---|---|---|---|---|
| | Btu/lb AF | % | Btu/lb AF | % | Btu/lb AF | % |
| Heat Outputs: | | | | | | |
| IIIa. Net Heat in Primary Steam | 3,133.69 | 58.62 | 2,357.14 | 51.34 | 2,534.45 | 56.41 |
| IIIb. Net Heat in Blowdown | 94.70 | 1.77 | 47.43 | 1.03 | 47.79 | 1.06 |
| IIIc. Net Heat in Cooling System | 150.57 | 2.82 | 129.77 | 2.83 | 120.59 | 2.68 |
| Subtotal +ε | 3,378.96 | 63.21 | 2,534.34 | 55.20 | 2,702.83 | 60.15 |
| Heat Losses: | | | | | | |
| IVa. Sensible Heat in Dry Flue Gas | 624.66 | 11.69 | 408.12 | 8.89 | 569.62 | 12.68 |
| IVb. Sensible & Latent Heat in Flue Gas Moisture | 712.22 | 13.32 | 750.04 | 16.34 | 694.22 | 15.45 |
| IVc. Radiation & Convection Losses | 221.93 | 4.15 | 198.68 | 4.33 | 169.07 | 3.76 |
| IVd. Unburnt Carbon in Residue | 355.12 | 6.64 | 702.34 | 15.30 | 356.25 | 7.93 |
| IVe. Sensible Heat in Dry Residue | 1.68 | 0.03 | 1.54 | 0.03 | 2.50 | 0.06 |
| IVf. Sensible Heat in Residue Moisture | 8.40 | 0.16 | 6.45 | 0.14 | 7.77 | 0.17 |
| IVg. Sensible Heat in Quench Overflow | 54.92 | 1.03 | 45.85 | 1.00 | 57.08 | 1.27 |
| IVh. Reserved | | | | | - | - |
| Subtotal +ε | 1,978.84 | 37.02 | 2,113.02 | 46.03 | 1,856.51 | 41.32 |
| Heat Credits: | | | | | | |
| Va. Sensible Heat in Dry Comb. Air | -15.90 | -0.30 | 14.47 | 0.31 | 18.37 | 0.41 |
| Vb. Sensible Heat in Air Moisture | - 0.01 | 0.00 | 0.44 | 0.01 | 0.57 | 0.01 |
| Vc. Sensible Heat in Fuel[3] | - 4.51 | -0.08 | 1.34 | 0.03 | 2.59 | 0.06 |
| Vd. Energy from Furnace/Boiler Fans | +16.32 | +0.31 | 15.25 | 0.33 | 22.74 | 0.51 |
| Ve. Sensible Heat in Evaporated Water | + 1.84 | +0.03 | 1.82 | 0.04 | 1.95 | 0.04 |
| Vf. Sensible Heat in Quench Overflow | +41.26 | +0.77 | 45.85 | 1.00 | 42.21 | 0.94 |
| Subtotal -ε | +39.00 | +0.73 | 79.17 | 1.72 | 88.43 | 1.97 |
| Total ε | 5,318.80 | | 4,568.19 | | 4,470.91 | |
| Unaccounted for Losses[4] | 26.73 | 0.50 | 22.96 | 0.50 | 22.47 | 0.50 |
| Grand Total εε | 5,345.53 | 100.00 | 4,591.15 | 100.00 | 4,493.38 | 100.00 |

Notes: (1) Generally, "Section 5: Computation of Results" in PTC 33-1978 served as the basis for the supporting calculation. See [3] for details.
(2) Tires were cofired at 7.4% by weight.
(3) No fossil fuel was fired in auxiliary burners.
(4) Unaccounted for losses set at only 0.5% because of the highly detailed and complete analysis above.

TABLE 4b HCRRF-RESULTS OF BAC ANALYSES[1] - SECONDARY TEST PERIODS

| Test Period | September 1990 | | August 1991 | |
|---|---|---|---|---|
| | Btu/lb AF | % | Btu/lb AF | % |
| Heat Outputs: | | | | |
| IIIa. Net Heat in Primary Steam | 2,028.83 | 43.79 | 2,396.71 | 51.66 |
| IIIb. Net Heat in Blowdown | 47.96 | 1.04 | 96.72 | 2.08 |
| IIIc. Net Heat in Cooling System | 118.30 | 2.55 | 103.24 | 2.23 |
| Subtotal +$\varepsilon$ | 2,195.09 | 47.38 | 2,596.67 | 55.97 |
| Heat Losses: | | | | |
| IVa. Sensible Heat in Dry Flue Gas | 604.44 | 13.05 | 523.28 | 11.28 |
| IVb. Sensible & Latent Heat in Flue Gas Moisture | 702.34 | 15.16 | 756.63 | 16.31 |
| IVc. Radiation & Convection Losses | 157.13 | 3.39 | 160.00 | 3.45 |
| IVd. Unburnt Carbon in Residue | 951.26 | 20.53 | 604.69 | 13.03 |
| IVe. Sensible Heat in Dry Residue | 1.68 | 0.04 | 1.96 | 0.04 |
| IVf. Sensible Heat in Residue Moisture | 8.60 | 0.19 | 7.10 | 0.15 |
| IVg. Sensible heat in Quench Overflow | 44.08 | 0.95 | 55.20 | 1.19 |
| IVh. Reserved | | | | |
| Subtotal +$\varepsilon$ | 2,469.53 | 53.31 | 2,108.86 | 45.45 |
| Heat Credits: | | | | |
| Va. Sensible Heat in Dry Comb. Air | 7.26 | 0.16 | 24.97 | 0.54 |
| Vb. Sensible Heat in Air Moisture | 0.12 | 0.00 | 0.85 | 0.02 |
| Vc. Sensible Heat in Fuel[2] | 0.00 | 0.00 | 3.76 | 0.08 |
| Vd. Energy from Furnace/Boiler Fans | 12.98 | 0.28 | 14.12 | 0.30 |
| Ve. Sensible Heat in Evaporated Water | 0.95 | 0.02 | 2.17 | 0.05 |
| Vf. Sensible Heat in Quench Overflow | 33.06 | 0.71 | 43.04 | 0.93 |
| Subtotal −$\varepsilon$ | 54.37 | 1.17 | 88.91 | 1.92 |
| Total $\varepsilon$ | 4,610.25 | | 4,616.62 | |
| Unaccounted for Losses[3] | 23.17 | 0.50 | 23.20 | 0.50 |
| Grand Total $\varepsilon\varepsilon$ | 4,633.42 | 100.00 | 4,639.82 | 100.00 |

Notes:
(1) Generally, "Section 5: Computation of Results" in PTC 33-1978 served as the basis for the supporting calculation. See [3] for details.
(2) No fossil fuel was fired in auxiliary burners.
(3) Unaccounted for losses set at only 0.5% because of the highly detailed and complete analysis above.

TABLE 5 HCRRF - MAJOR PERFORMANCE PARAMETERS FROM BAC

| Test Period | Load Factor $LFg$[2] % | Higher Heating Value HHV Btu/lb | System Thermal Efficiency[3] $\eta_t$ % | Specific Steaming Rate SSR lb/lb | Enthalpy Difference $\Delta h$ Btu/lb | Specific Ash Rate SAR lb/lb |
|---|---|---|---|---|---|---|
| Jan. 1988[1] | 91.14 | 5,346 | 58.62 | 3.109 | 1,007.9 | 0.4200 |
| Sept. 1990 | 114.47 | 4,633 | 43.79 | 2.056 | 986.8 | 0.4154[4] |
| Aug. 1991 | 102.13 | 4,640 | 51.66 | 2.411 | 993.9 | 0.3505[4] |
| Aug. 1992 | 85.26 | 4,591 | 51.34 | 2.355 | 1,000.8 | 0.4114 |
| June 1993 | 96.33 | 4,493 | 56.40 | 2.549 | 994.4 | 0.4489[4] |
| Average $\bar{x}_5$ | - | - | 52.36 +12 -16% | - | 996.8 ±1% | - |

Notes:
(1) Includes cofiring of tires at 7.4% by weight.
(2) Based on the average hourly fuel mass flow rate in the facility, i.e. the total amount of fuel actually charged divided by rated capacity.
(3) Includes unaccounted for losses.
(4) Monthly rates as substitute for BAC test period.

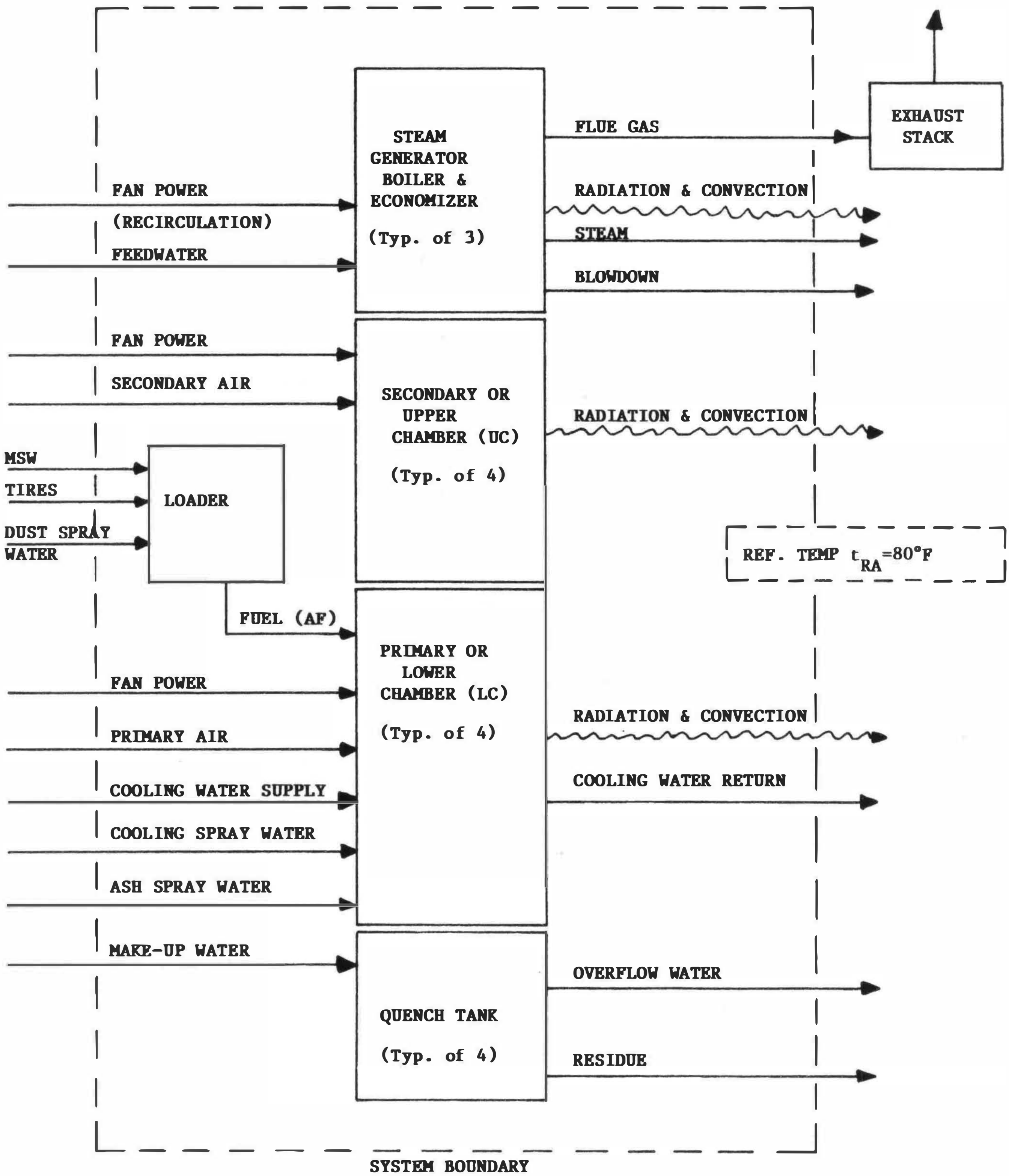



FIG 1 HCRRF - THERMODYNAMIC INPUT-OUT MODEL
FOR BAC ANALYSIS OF TWO-STAGE COMBUSTORS

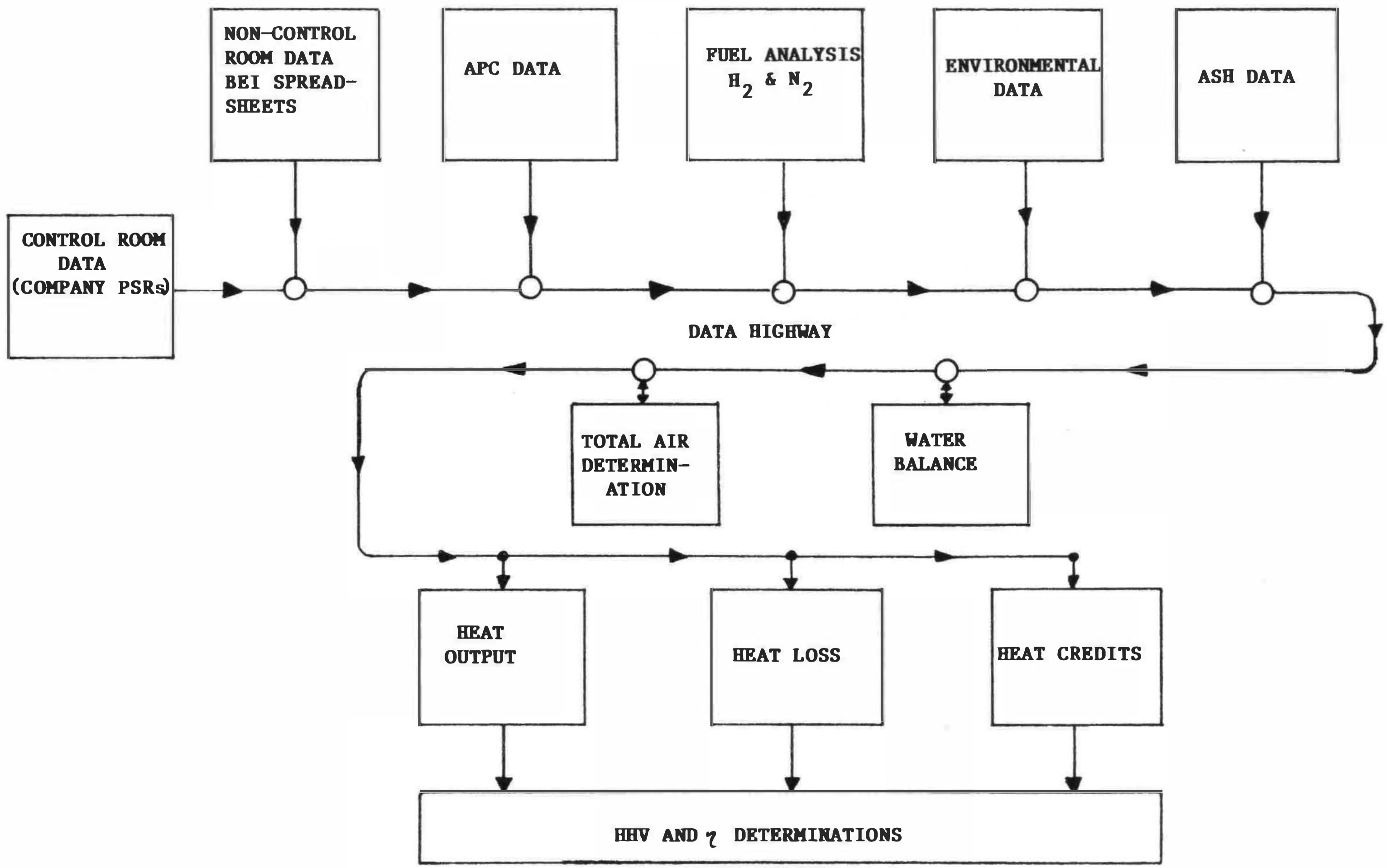
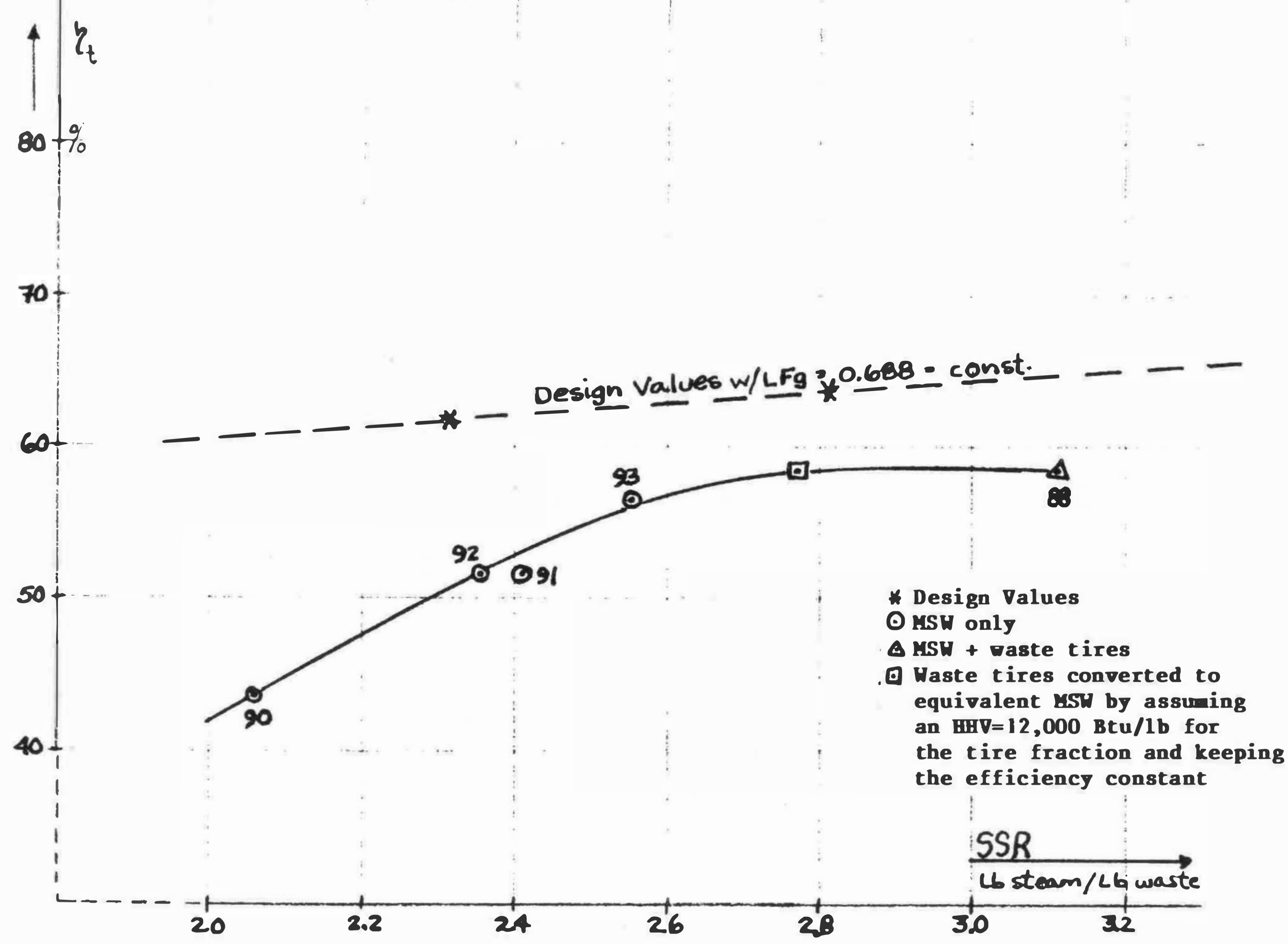



FIG 2 HCRRF - DATA INPUT AND METHODOLOGY FLOW CHART FOR BAC ANALYSIS

FIG 3 RELATIONSHIP BETWEEN $\eta_t$ AND SSR DURING BAC TEST PERIODS



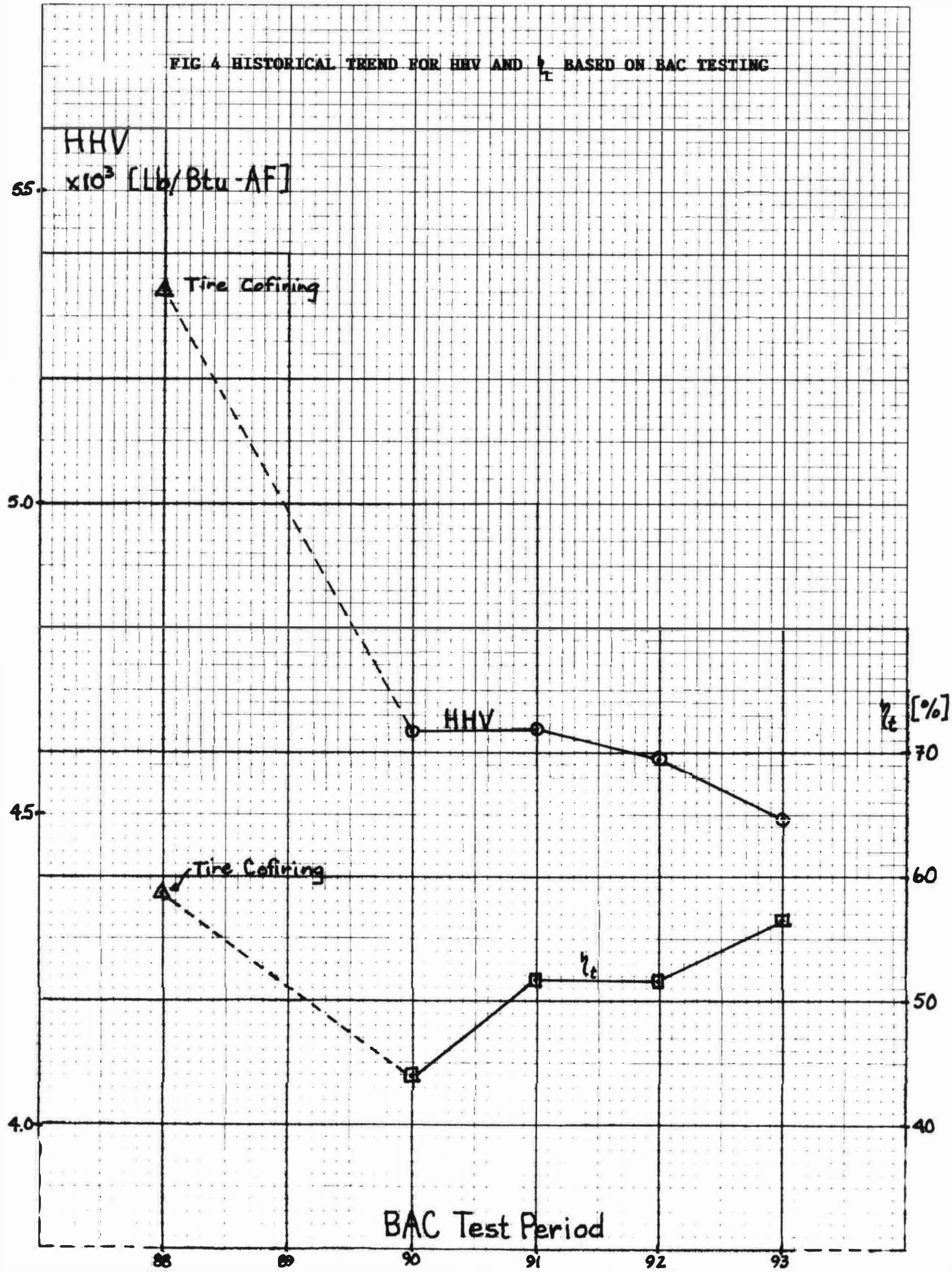



FIG 4 HISTORICAL TREND FOR HHV AND $\eta_t$ BASED ON BAC TESTING

FIG 5 VARIATION IN HHV AS A FUNCTION OF THE RECYCLING RATE FOR VARIOUS ANALYTICAL MODELS