International
Fertilizer Industry
Association

IFA Technical Conference

Venice, Italy

2-4 October 1990

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STEAM AND POWER BALANCES IN AMMONIA PLANTS AND AMMONIA-UREA COMPLEXES

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Abstract

The paper reviews the overall energy balance for ammonia plants and for ammonia-urea complexes. Different process configurations in the ammonia plant will be considered. The efficiency of steam turbine power cycles and gas turbine power cycles will be discussed, and it is shown at which conditions gas turbines can be effectively integrated into the overall steam and power balance for an ammonia plant or an ammonia-urea complex. Cases are given for design of new units as well as for revamp of existing units by modification of the steam-power system with or without installation of gas turbines.

Introduction

The paper discusses the steam and power balances of ammonia plants alone and in combination with a urea plant. The basis for the discussion is a natural gas based low energy ammonia plant. Two situations are considered:

- A "stand-alone" ammonia plant with dedicated utility installations comprising a unit which does not import or export power or steam to/from other installations.
- A situation where a large energy consumer - exemplified by a urea plant - is located on the same site so that the ammonia plant can be designed for a significant steam export.

In order to facilitate the discussion, fixed values will be assumed for energy consumption in the utility and offsite installations and in the urea plant. The relevant figures are given in Table 1 and Table 2. The figures may be considered typical; there may, obviously, be significant variations in the consumption in the urea plant depending on process type and especially in the utility and offsite installations depending on local factors. It is, however, not the purpose of this presentation to consider such variations.

Steam Production in Ammonia Plants

An ammonia plant consists of a combination of energy consuming and energy producing process units. Energy is mainly required for the initial conversion of feedstock by steam reforming. This energy is supplied by external combustion of fuel in the primary reformer furnace and by internal combustion in the secondary reformer. Energy is also required for generation of process steam, for preheat of process streams, and in most cases for regeneration of solvent in a carbon dioxide removal unit. Furthermore, motive power is required for compression of feed streams and synthesis gas, for recovery and refrigeration of product ammonia, and for other purposes, e.g. pumps and blowers. Energy for these purposes is obtained by recovery of waste heat from the process units, if necessary supplemented by extra firing in auxiliary installations and/or by imported power.

In all large, modern ammonia plants waste heat is recovered by production of high pressure steam, and this steam is used partly as process steam, partly for generation of power in steam turbines. Waste heat is available in the reforming section, the shift section, and the synthesis loop. As an example, Figure 1 shows the steam generation in an existing 1000 MTPD ammonia plant (Ref. 1). The total heat transferred to the steam generation for boiler feed water preheat, boiling and steam superheating is in this plant 125 Gcal/h corresponding to production of 188 t/h superheated high pressure steam (110 at, 510°C).

The use of steam in the same 1000 MTPD ammonia plant is illustrated in Figure 2. This specific plant is part of a large complex with steam grids at several pressure levels, and the ammonia plant exports steam at 38 at, at 22 at (process steam to a urea plant) and 3.5 at. The use of steam is fairly typical for a modern low energy plant with large compressors and pumps on steam turbines.

The steam production in an ammonia plant may, for the same basic process lay-out, be varied within certain limits by adjusting various process parameters. Some examples are:

- Introduction of combustion air preheat will reduce the firing to the reformer and consume part of the heat available in the reformer flue gas, thus reducing the heat available for steam production.

- Increase of methane content in the product gas from the reforming section will reduce the firing to the primary reformer, again reducing the amount of heat available in the reformer flue gas for steam production.

- Reduction of the steam to carbon ratio at inlet reforming section will influence the steam system in several ways. The firing to the reformer will be only marginally affected, since higher temperature is required to obtain the same conversion of methane. Less heat will be available in the product gas from the reforming section, due to the reduced gas flow, and the amount of low level heat released by condensation of excess water from the process gas will be considerably reduced. This heat is used for boiler feed water preheating and for reboiling in the carbon dioxide removal unit, and low steam to carbon ratio is therefore most attractive in combination with carbon dioxide removal processes with low reboiler duty. The consumption of steam for the process will be reduced, and the overall result of a reduction of the steam to carbon ratio will most often be an increase in the amount of steam available for other purposes.

- Introduction of improved heat recovery in the synthesis loop, e.g. by introducing the Topsøe S-250 reactor configuration, where part of the heat of reaction is recovered in a boiler or superheater installed between two synthesis converters.

This increases the amount of heat available and also helps to adjust the amount of heat available at required temperature levels.

By adjustments as outlined above and by other measures it is possible for a given case to adjust the steam production to a desired level above a minimum which depends on the process concept. It is of course always possible by increasing the firing to raise the steam production to any desired level above the minimum.

The minimum steam production will, for a "conventional" low energy process, be slightly below 3 t per t ammonia (of course still assuming the most efficient recovery of the available heat). This amount of steam will roughly correspond to the amount required for the process and for the major drivers, and the plant will thus be in steam balance (a situation which may not always be desirable) and requires only import of electric power for minor drivers, etc. The total energy consumption inside battery limits for a natural gas based plant designed for this situation and using the Topsøe Low Energy Process will be 6.7 Gcal/t ammonia assuming a location in Western Europe. The consumption of natural gas will be 6.6 Gcal/t ammonia.

Other process concepts will have different characteristics. In the following two out of many possible features will be considered.

- In some cases extra firing is introduced inside the ammonia plant battery limits by using a gas turbine as driver for one of the large compressors, usually the process air compressor. A more detailed discussion of the use of gas turbines is given below. At this point it shall only be mentioned that the extra firing increases the minimum steam production - assuming efficient heat recovery - to a level in excess of the plant's own requirement. The use of gas turbines in ammonia units is therefore only relevant when steam export is required.

- The use of heat exchange reforming in ammonia production has recently gained much attention. It is not the purpose here to discuss this process concept. Basically it may be pointed out that heat exchange reforming fundamentally changes the waste heat balance of the process. Most of the high temperature heat will, via the heat exchange reformer, be returned to the process and will thus not be available for steam production, and an excess of low temperature heat will be available (e.g. for production of medium- or low pressure steam), thus reducing the efficiency of the steam production. This means that a plant using heat exchange reforming cannot produce sufficient steam to supply the energy required to drive compressors etc. from inside battery limits, and the overall energy efficiency of the concept will depend entirely upon the efficiency of the auxiliary energy generation.

Steam/Power System of Ammonia Plants

The steam/power system of an ammonia plant may be considered as an open system with import/export of steam and power from/to the surroundings. An example is shown in Figure 3 which illustrates the balance for the plant referred to in Figures 1 and 2.

It is customary to quote a so-called "net energy consumption" for an ammonia unit based on figures such as those shown in Figure 3. In order to do this, standard energy values must be assigned for power and for steam at various conditions. The calculation for the plant referred to in Figures 1, 2 and 3 is shown in Table 3. The relevance of the values used for power and steam is dicussed in a later paragraph.

A more complete and realistic understanding of the energy consumption in an ammonia plant or an ammonia-urea complex may be obtained by "closing" the energy balance, i.e. by considering the units as "stand-alone" installations which do not import or export power or steam across the battery limits. If the battery limits are well-defined this consideration will allow a realistic comparison of different process schemes.

Simplified examples for a stand-alone ammonia plant and an ammonia-urea complex, in both cases with required utility installations and off-sites, are shown in Figures 4 and 5. (Unfortunately, complete data from the complex containing the plant referred to in Figures 1, 2 and 3 and Table 3 are not available. The data in Figures 4 and 5 - and the in remaining part of this presentation - are therefore based on studies done in our company for a plant to be located in India).

Figure 4 illustrates the stand-alone ammonia plant. The ammonia unit is a Topsøe low energy plant where operating conditions have been adjusted to obtain a steam production which matches the requirements of the complex. The energy balance is closed by expansion of the steam in a turboalternator producing the required power. Figure 5 shows the balance for an ammonia-urea complex. The process lay-out in the ammonia unit is basically the same as in the stand-alone plant. The production of carbon dioxide is adjusted by production of excess synthesis gas which is used as fuel in the reformer. The energy balance is closed by production of power and steam in a dedicated unit. The energy consumption in this unit depends on the type of installation as indicated on the figure.

From the data given in Figures 4 and 5 a few important points may be noted:

- The consumption of natural gas is higher in a plant supplying ammonia and carbon dioxide for urea production than in a stand-alone ammonia plant of the same capacity, due to the production of the stoichiometric amount of carbon dioxide for full conversion of ammonia to urea.

- The steam production in the ammonia unit may - as discussed in the preceding paragraph - be adjusted within certain limits, and also the consumption of power may be varied from case to case . In the example the steam export from the ammonia plant is sufficient to produce all required power in a turboalternator. In other cases additional steam must be produced in an auxiliary boiler.

- In the ammonia-urea complex the steam and power consumption is so large that it significantly exceeds what can reasonably be produced from the waste energy available in a low energy ammonia plant. The extra steam and power is in the example produced in dedicated installations. Alternatively the ammonia plant lay-out may be changed, e.g. by use of gas turbines as direct driver instead of steam turbines - and different overall energy efficiencies will result. The use of gas turbines in ammonia plants will be discussed further below.

Efficiency of Power Generation via Steam Cycle

The efficient use of waste heat for steam production and the efficiency of power production from the steam is of major importance for the overall energy efficiency of an ammonia plant. Important parameters are the availability of waste heat at the required temperature levels and the steam pressure and superheat temperature. The points may be illustrated by the data shown in Table 4.

It will be seen that efficiency is of course highest when steam temperature and pressure are highest. It is further seen that the requirement for heat at various temperature levels varies significantly with steam conditions.

The difference in energy efficiency is quite significant. The figures in the lowest line are calculated for exactly the same process lay-out; the only difference is the conditions in the steam system. It is seen that the energy consumption will for the same process concept increase by 0.4 Gcal/MT ammonia or by more than 5% when the steam system is changed from high pressure to medium pressure steam.

The energy value of steam at different conditions is normally given as the calorific heat content (enthalpy content) with 0°C as reference (cfr. Table 3). It could, with reference to Table 4, also be argued that the reference should be the temperature of the boiler feed water at inlet first boiler feed water preheater - assuming that heat below this temperature is abundantly available. This reasoning would, however, only be correct for steam produced direct in boiler and superheater, and it would still be based on the dubious assumption that heat at different temperature levels has the same "value".

In many cases steam at medium or low pressure is produced by expansion of high pressure steam in a turbine. If this is the case the power produced in the turbine must be taken into consideration when the "value" of the steam is computed. Energy values of steam at various conditions calculated on this basis are compared to "full calorific value" in Table 5. The conclusion is that to obtain a realistic evaluation of the energy consumption in a plant, a closed steam/power balance should be considered, or the value of steam should be a site specific energy value (or better money value). Alternatively, the amounts and conditions for imported and exported steam and power should be clearly stated (cfr. Table 3).

Efficiency of Power Generation via Gas Turbines

It is not the purpose of this presentation to discuss gas turbine installations as such. They will be considered "black box installations" with typical features, and the energy efficiency will be illustrated by showing how they can at different conditions be integrated into an ammonia plant.

A typical gas turbine installation may be as shown in Figure 6. Air is compressed, normally to 10-12 kg/cm^2g, and mixed with fuel at this pressure in combustion chambers . The combustion gases at 900-1100°C are expanded in a turbine which drives the air compressor and a power generator. The exhaust from the turbine will be available at 450-550°C. The heat content in this gas is used for steam production which may be exported from the unit, to close the steam balance for the complex. The efficiency of such a co-generation unit depends on the steam pressure and the ratio between steam and power production. As examples the fuel consumption for production of 9 MW power plus different amounts of export steam is shown in Figure 7 for different types of installations. Clearly, these values can only be considered typical. For a specific case, an evaluation must be based on the expected performance of a specific type of gas turbine operating at specified conditions. Alternatively, the steam may be expanded in a turbine producing additional power, usually referred to as a combined cycle power plant. The efficiency of a combined cycle power plant operating at optimum conditions may be very high. Figures above 50% have been quoted. It is, however, not realistic to expect such high efficiency in a utility installation in an ammonia-urea complex. The main reason is that the unit will normally be relatively small and operate at part load only. Our studies related to specific cases have indicated that an efficiency of 37% may be reasonably assumed.

A wide range of gas turbines are available with power output from less than 1 MW to more than 100 MW. Each turbine may in addition to the power output be characterized by the heat rate, i.e. the amount of fuel required per unit power produced, and by the temperature of the exhaust from the expansion turbine. Typical heat rates range from slightly below 3000 to slightly above 4000 kcal/kWh. The heat rate and the exhaust temperature will furthermore vary with load and with local conditions (standard values are given at so-called ISO-conditions, i.e. 15°C and sea level elevation).

Use of Gas Turbines in Ammonia Units and Ammonia-Urea Complexes

As mentioned in the previous paragraphs gas turbines may be used in several ways in ammonia plants. In the following three typical concepts will be considered:

- The gas turbine is used in a co-generation unit which serves to close the steam-power balance in an ammonia-urea complex. This situation is considered in Figure 5.

- The gas turbine is used as driver for the process air compressor, and the hot exhaust from the gas turbine is used as combustion air in the reformer. Additional power is produced in a power generation unit which may be a combined cycle power plant or a boiler and steam turbine installation. In all cases the power production unit should be designed to utilize possible excess steam from the ammonia unit. This concept is illustrated in Figure 8.

- The gas turbine is used as driver for the process air compressor, and the exhaust from the gas turbine is used for steam production. Additional firing is provided to adjust the steam production as required. Additional power is produced from steam in a turboalternator. This concept is illustrated in Figure 9. Alternatively, steam may be produced from the exhaust without additional firing, and the steam and power balance is closed by a co-generation unit.

The energy consumptions for the various cases are compared in Table 6. The energy consumption has been calculated for each case for the ammonia unit as an "open" system with import of power and export of steam as indicated. The energy value of power and steam has been calculated using standard conversion factors as indicated.

The energy consumption has also been calculated for the entire complex as a "closed" system importing only feedstock and fuel.

The following can be seen from Table 6 (note, however, that "typical" figures have been used for efficiencies of power production, etc. in different types of units. The conclusions drawn from Table 6 may not be universally applicable):

- The energy consumption of a stand-alone ammonia plant (Figure 4) is lower than that of an ammonia-urea complex of similar design (Figure 5) also when the ammonia plant is considered as an "open" system. This is because of the required extra production of carbon dioxide.

- The energy consumption for the "open" system is lowest when the steam export is highest (Figure 8). This is of course due to the high energy value used as credit for steam export. This seems fairly obvious, but it is surprising how often so-called "net energy consumption" is taken at face value without consideration for details such as steam credit, etc.

- The concept of using a gas turbine as driver for the process air compressor is very energy efficient. There is, however, no significant difference between the cases where the exhaust is used as combustion air in the reformer (Figure 8) and the cases where the exhaust goes to a steam boiler (Figure 9).

- A very low energy consumption is obtained for each concept when a gas turbine is combined with a high pressure steam boiler (Figure 5d and Figure 9b).

- The lowest energy consumption of all (Figure 8c) is obtained for a somewhat complicated and certainly rather expensive concept featuring two gas turbines, one as direct driver for the process air compressor and one as part of a combined cycle power plant. A less complex - and also cheaper - concept (Figure 9b) is almost as energy efficient. This concept features a gas turbine installation as illustrated in Figure 10 with a gas turbine as direct driver for the process air compressor and topped with a high pressure boiler with auxiliary firing to adjust steam production. The BFW preparation and preheating for this boiler may be integrated with the corresponding system for the process boilers in the ammonia unit, thus optimizing the recovery of low grade heat. The steam produced is partly expanded in a turbine for power production, partly exported as required to other units in the complex.

The concept illustrated in Figure 10 is flexible and may be adjusted to different operating situations. It also provides for easy start-up of the entire complex. It probably represents the optimum integration of a gas turbine into an ammonia-urea complex or a similar installation.

Gas Turbines in Revamp Projects

The options for use of gas turbines in revamp projects does not in principle differ from the options in new plants. An example may be sufficient to indicate the possibilities.

Table 7 illustrates results from a study on revamp of an existing ammonia plant. By replacing a steam turbine driver for the air compressor with a gas turbine and using the exhaust from the gas turbine with additional firing to produce MP steam in an auxiliary boiler a saving of 14.3 Gcal/h or 0.25 Gcal/MT of ammonia could be obtained in this 1350 MTPD ammonia plant without changing the steam and power production.

Reference 1: Tasrif, A.: "KALTIM-III, Indonesia's New Low Energy Ammonia Plant", presented at the Fertilizer Asia Conference & Exhibition, 15th - 18th October, 1989, Manila, The Phillippines.

Table 1
Ammonia-Urea Complex
Approximate Consumption Figures in Urea Production

Ammonia : 1350 MTPD
Carbon Dioxide : 37250 Nm^3/h
MP Steam : 95 t/h
Power : 2.7 MW

All figures are for a nominal 2300 MTPD urea plant.

Table 2
Assumed Consumption in Utility and Offsite Installations for a 1350 MTPD Ammonia Plant and a 2300 MTPD Urea Plant

	Stand-alone Ammonia Plant	Ammonia-Urea Complex
CW Pumps, TPH MP Steam	9.5	15.5
Other Utilities *, MW	1.5	2.0
Offsites **, MW	1.5	3.0

* BFW Preparation
Instrument Air
Inert Gas, etc.

** Storage, Bagging, Product Loading
Waste & Rain Water
Buildings, Lighting, Air Conditioning, etc.

Table 3
Average Performance Data Recorded During Test Run

	Performance Figures
Production:	
Ammonia (t/d)	1031
Carbon Dioxide (t/d)	1366
38 at steam (t/t NH_3)	(0.13)
20 at steam (t/t NH_3)	0.581
3.5 at steam (t/t NH_3)	0.548
Process condensate (t/t NH_3)	1.53
Steam condensate (t/t NH_3)	1.02
Consumption:	
Natural gas, LHV (Gcal/t NH_3)	7.641
Electric power (kWh/t NH_3)	28.6
Demineralized water (t/t NH_3)	4.31
Sea water (m^3/t NH_3)	210
Net consumption, Gcal/t NH_3 *	7.02 *

* Calculated by using the following conversion factors:

Power : 1 kWh = 2778 kcal
38 at steam : 1 kg = 759 kcal
20 at steam : 1 kg = 727 kcal
3.5 at steam : 1 kg = 672 kcal

The steam values correspond to full calorific value with water at 0°C as the basis.

Table 4
Energy Required for Steam Production

	1	2	3	4
Steam conditions:				
Pressure, kg/cm^{2}g	110	70	50	40
Temperature, °C	510	480	450	400
Quantity of heat required per kg steam * :				
BFW preheat, min. temp. °C	140-315	140-285	140-265	140-250
kcal	195	157	135	120
Boiling, min. temp. °C	340	310	290	275
kcal	324	377	405	424
Superheating, min. temp. °C	370-565	340-530	320-500	305-450
kcal	167	141	132	102
Total heat required, kcal/kg	686	675	672	646
Fuel required at 92% efficiency, kcal	746	734	730	702
Energy from turbines, kWh/kg **	0.280	0.260	0.248	0.229
Efficiency of steam/power cycle, %	32.3	30.5	29.2	28.0
Energy consumption in NH_3 plant, Gcal/MT	BASE	+0.18	+0.33	+0.40

* BFW at 132°C heated to 15°C below boiling point.
Losses on steam : 5 kg/cm^2, 5°C
Losses in exchangers : 1%
Boiler blow down : 1%

** Condensing turbine, $\eta = 78.5\%$, condenser pressure 0.12 kg/cm^2 a.

Table 5
Examples of Energy Values of Steam

	HP	MP	MMP	LP
Steam conditions:				
Pressure, kg/cm^{2}g	110	38	22	3.5
Temperature, °C	510	370	Sat.	Sat.
"Full calorific value", kcal/kg	810	752	669	655
Net value after expansion and saturation, kcal/kg *	746	575	437	280
% of "full calorific value"	92	76	65	43

* Lower pressure levels generated by expansion of HP steam. Power credited at 2778 kcal/kg. Assumed efficiency of turbines: HP → MP : 75%, all other 80%. BFW at 132°C.

Heat required per ton of HP steam: 686 kcal/kg. Efficiency of marginal firing: 92%.

Table 6
Energy Consumption for All Cases in Figures 4, 5, 8 and 9
(for description see the individual figures)

	Ammonia Unit as "Open" System ($Gcal/MT\ NH_3$)	Whole Complex as "Closed" System ($Gcal/MT\ NH_3$)
Figure 4	6.76	7.09
Figure 5a	6.98	8.69
5b	6.98	8.55
5c	6.98	8.52
5d	6.98	8.46
Figure 8a	6.43	8.35
8b	6.43	8.30
8c	6.43	8.26
Figure 9a	6.71	8.44
9b	6.71	8.30
9c	6.71	8.34

Energy values assumed:

Power : 2778 kcal/kWh
MP steam : 752 kcal/kg

Table 7
Revamp Study - Steam and Power Generation Example

Before revamp:

Auxiliary boiler produces 100 t/h MP steam
42 t/h steam to air compressor turbine (9.2 MW)

After revamp:

Gas turbine drives air compressor. Exhaust to
MP boiler with additional firing to produce
58 t/h MP steam

Fuel consumption:

Auxiliary boiler	:		71.2 Gcal/h
Gas turbine	:	36.6	
Additional firing	:	20.3	56.9 Gcal/h
Saving			14.3 Gcal/h

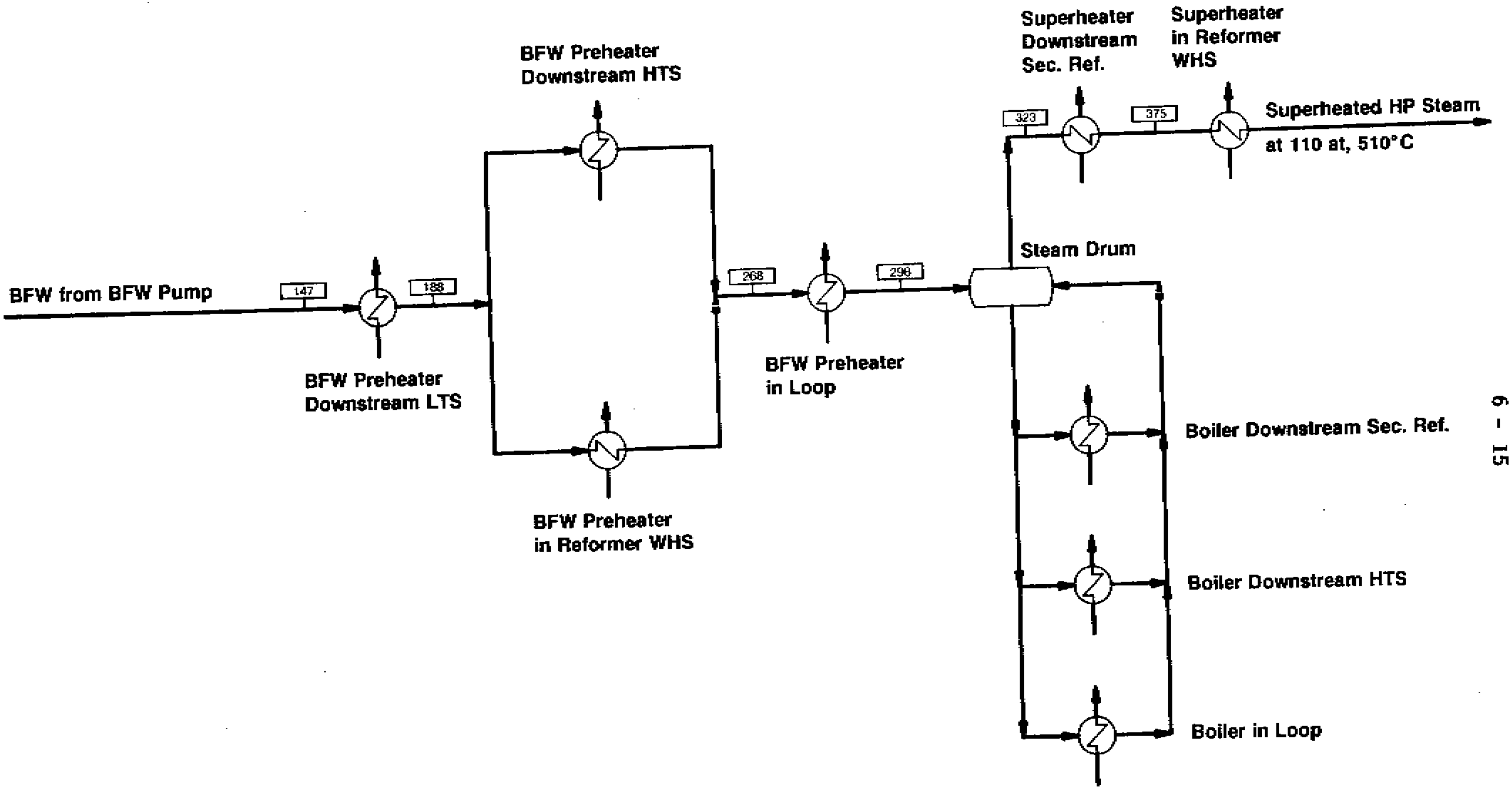


Figure 1
Steam Production in Existing 1000 MTPD Ammonia Plant

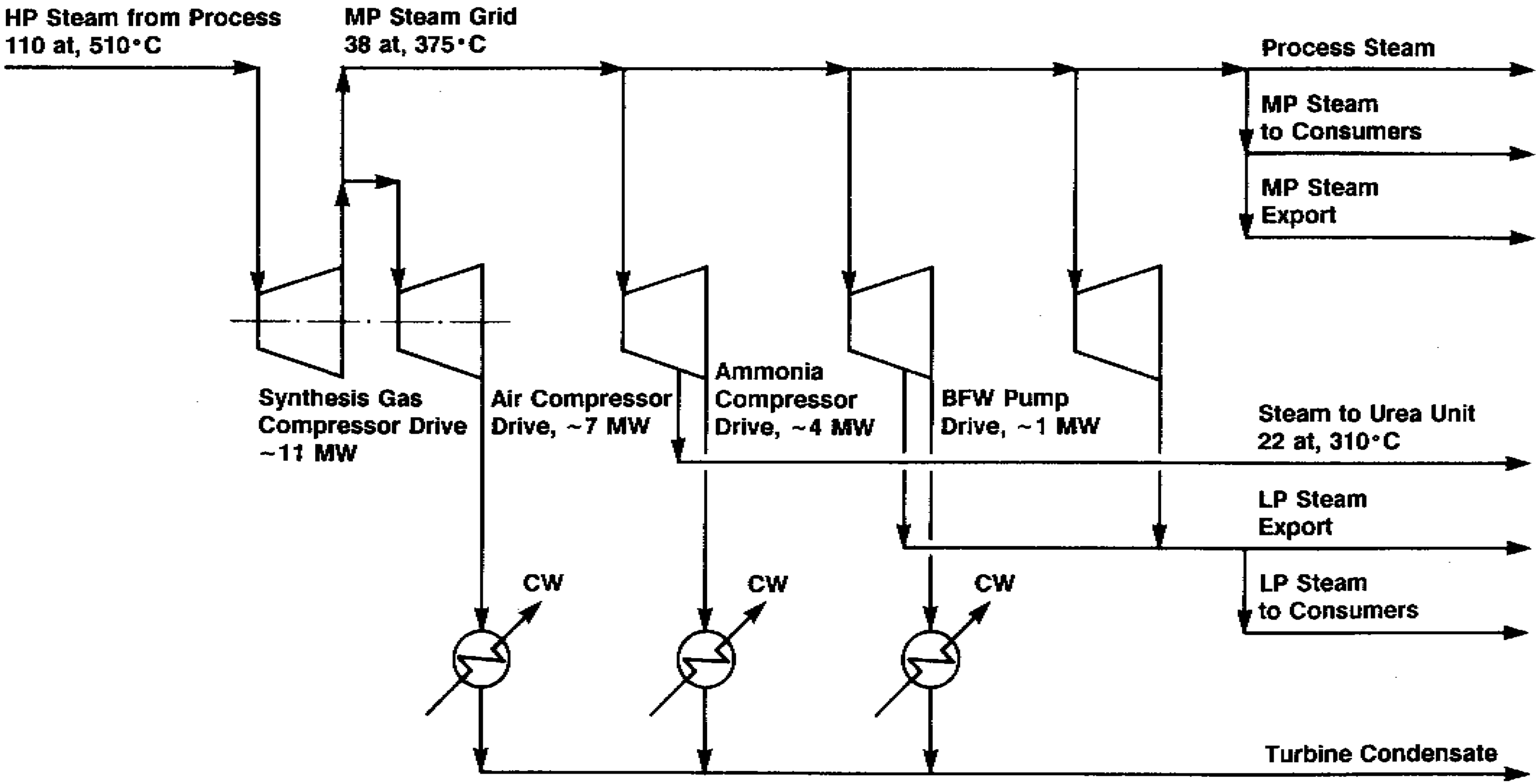
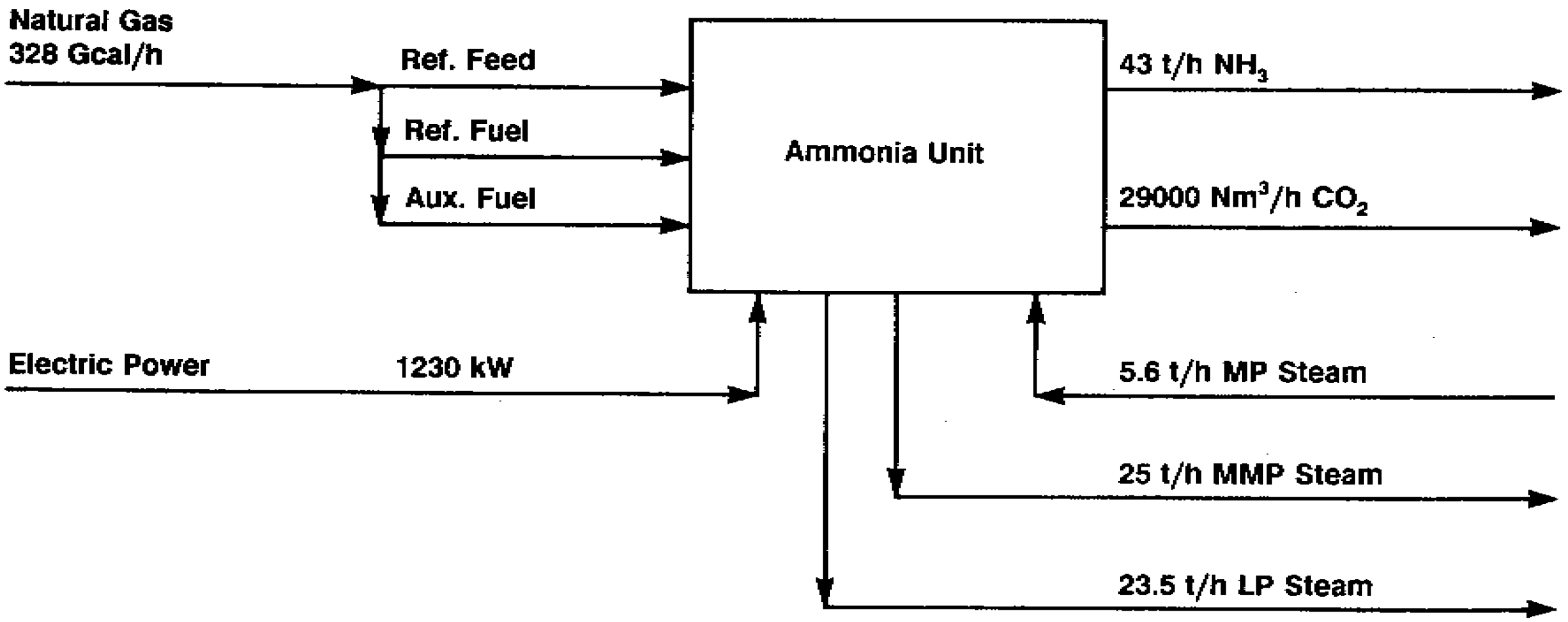


Figure 2
Steam Consumers in Existing 1000 MTPD Ammonia Plant



MP Steam : 38 kg/cm^2g, 370°C
MMP Steam : 20 kg/cm^2g, sat.
LP Steam : 3.5 kg/cm^2g, sat.

Figure 3
Energy Balance for Existing 1000 MTPD Ammonia Plant

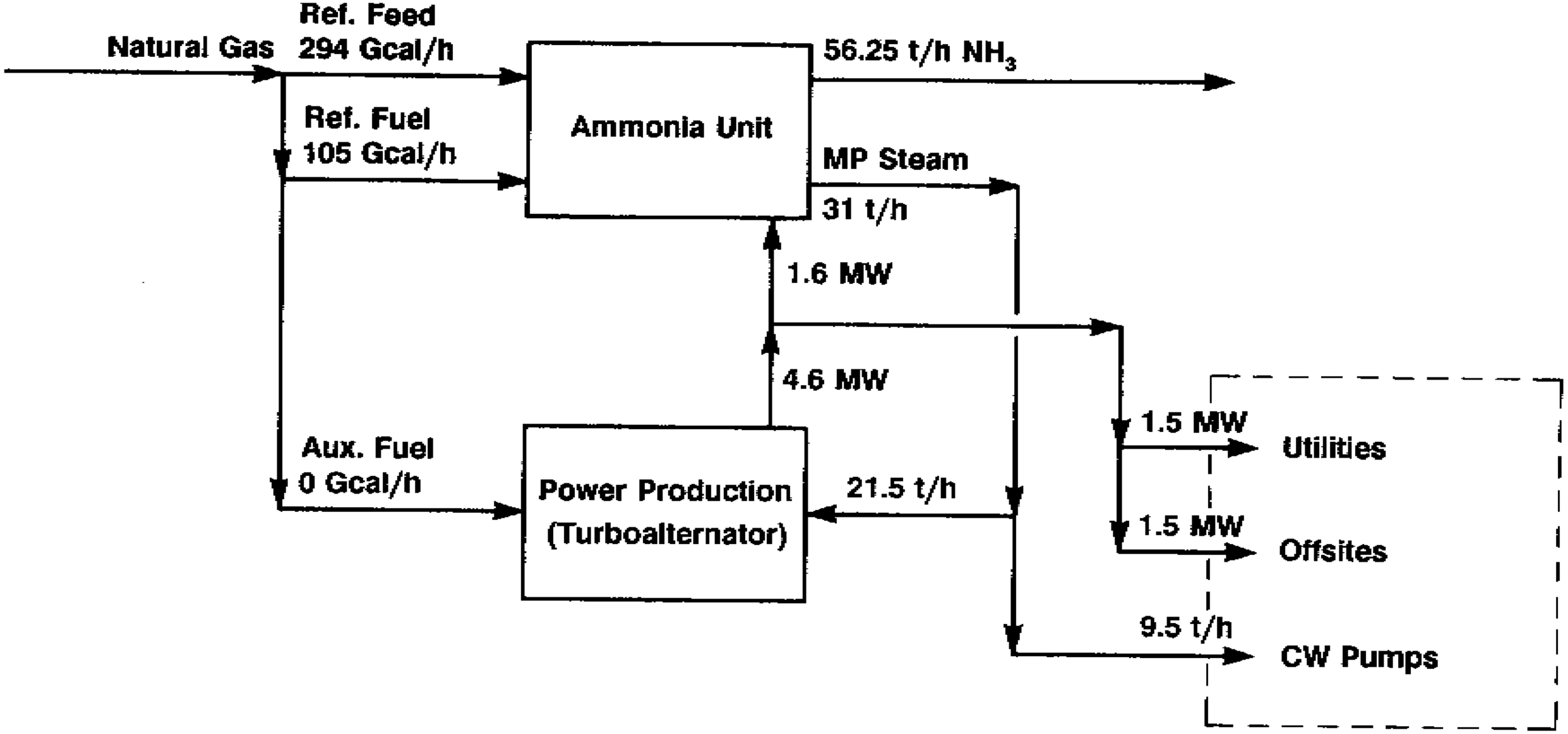
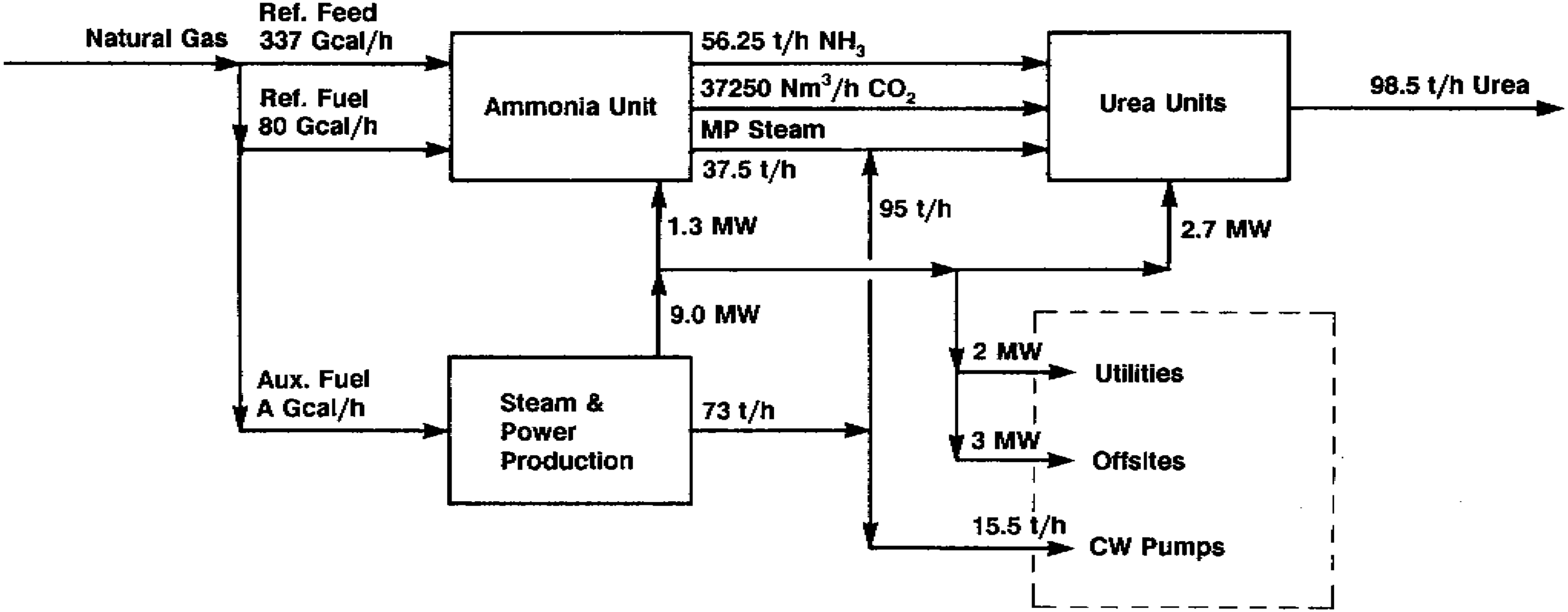


Figure 4
Energy Balance for Stand-alone 1350 MTPD Ammonia Plant



5a : MP Steam Boiler + Turboalternator : A = 72 Gcal/h
5b : HP Steam Boiler + Turboalternator : 64 Gcal/h
5c : Gas Turbine + MP Steam Boiler : 62 Gcal/h
5d : Gas Turbine + HP Steam Boiler : 59 Gcal/h

Figure 5
Energy Balance for Ammonia-Urea Complex
(1350 MTPD Ammonia/2300 MTPD Urea)
Conventional Process Concept

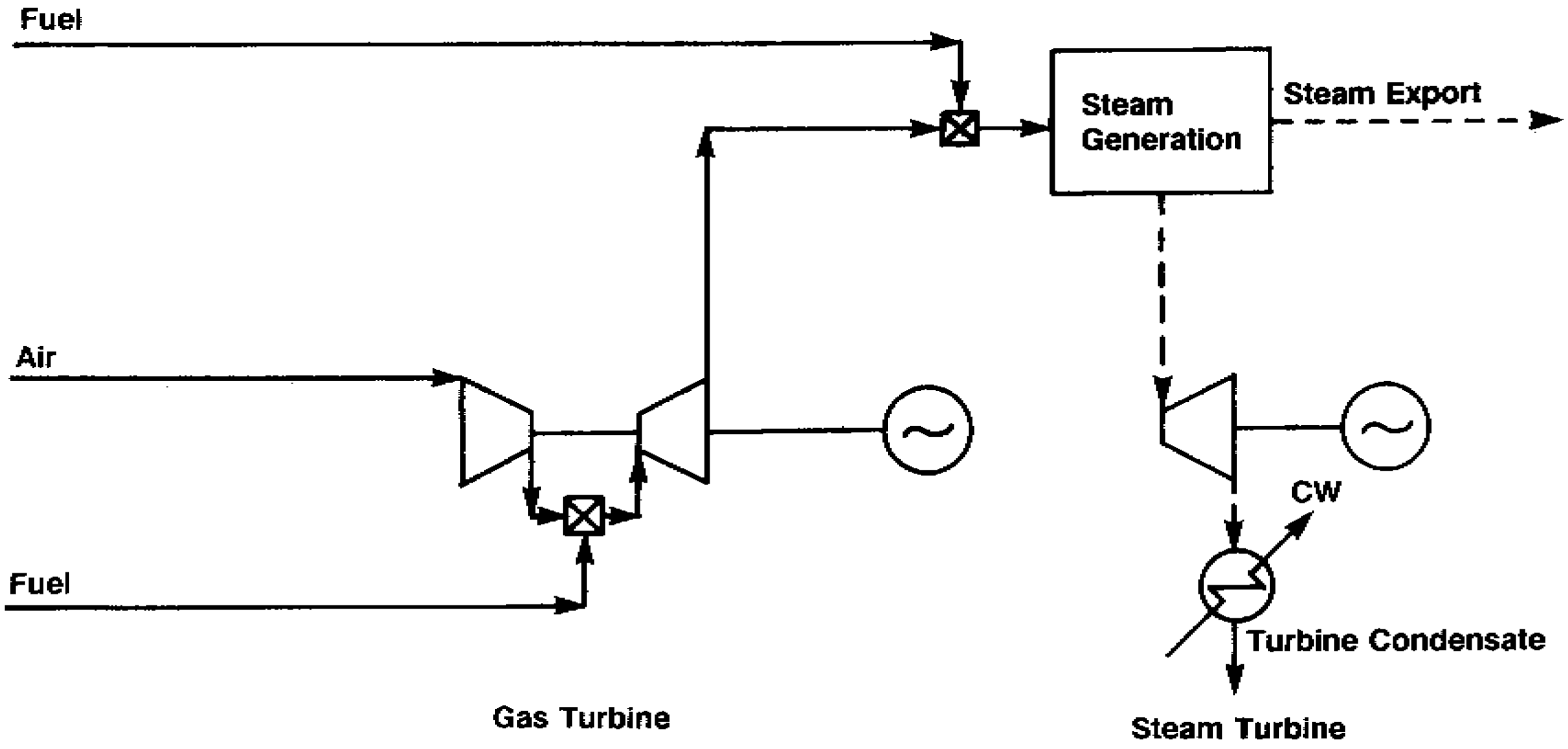


Figure 6
Principles of Gas Turbine Installations

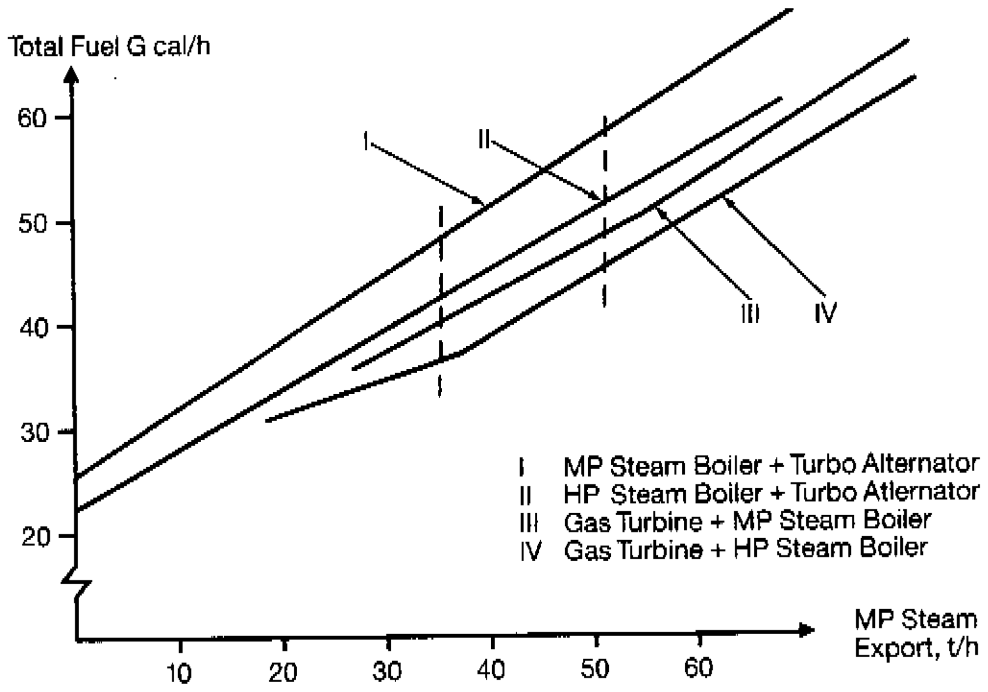
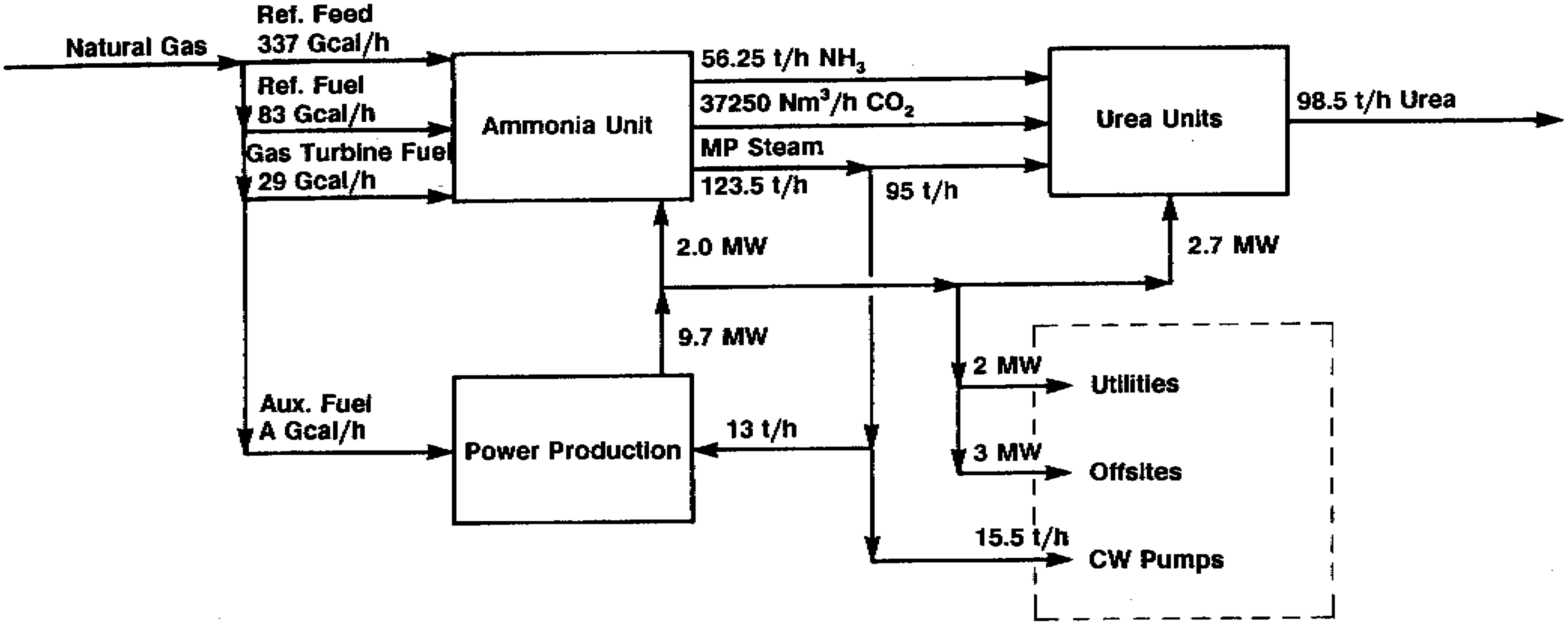
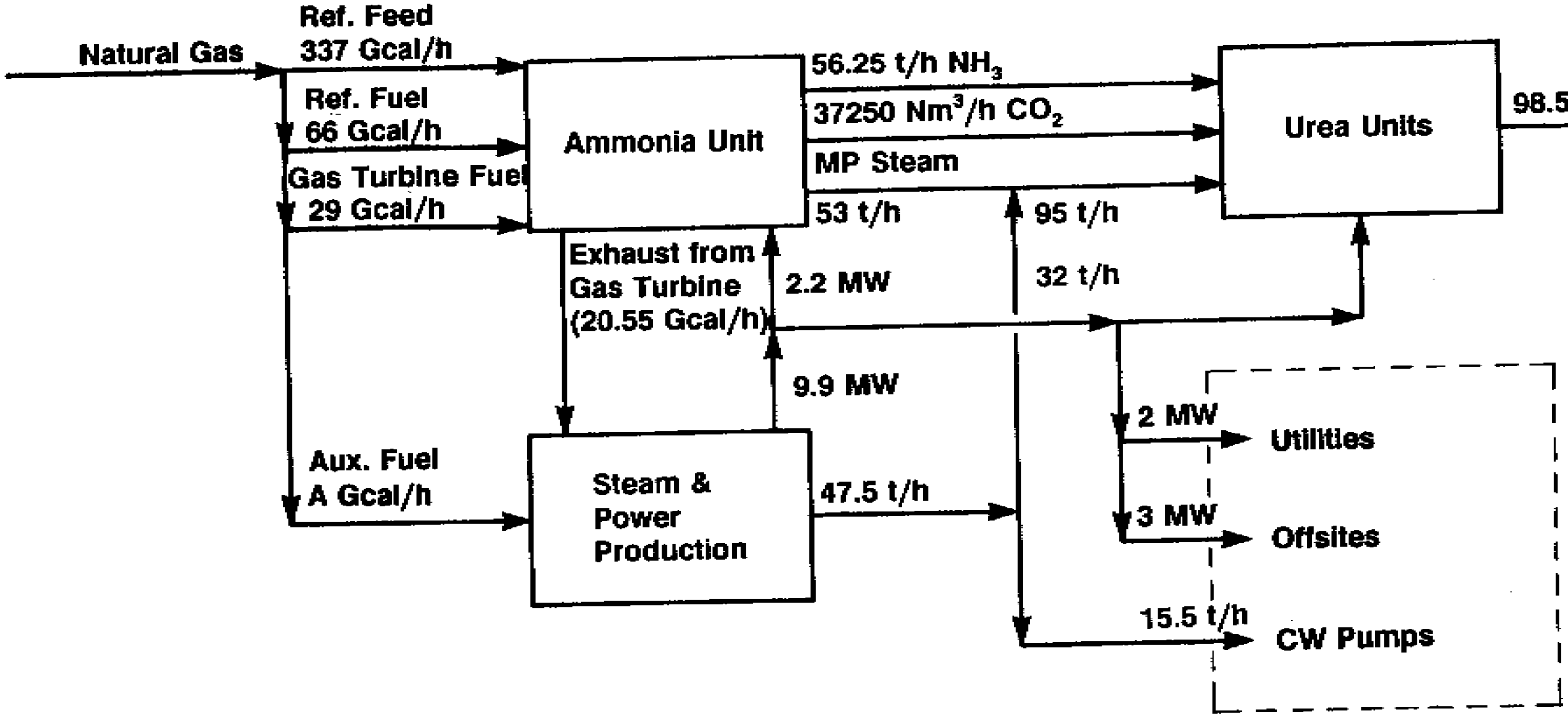


Figure 7
Total Fuel Consumption for Production of 9 MW Power + Additional MP Steam for Export



8a : MP Steam Boiler + Turboalternator : A = 20 Gcal/h
8b : HP Steam Boiler + Turboalternator : 18 Gcal/h
8c : Combined Cycle Power Plant : 15 Gcal/h

Figure 8
Energy Balance for Ammonia-Urea Complex
(1350 MTPD Ammonia/2300 MTPD Urea)
Air Compressor on Gas Turbine Driver
Exhaust to Reformer as Combustion Air



9a	:	MP Steam Boiler + Turboalternator :	A = 43 Gcal/h
9b	:	HP Steam Boiler + Turboalternator :	35 Gcal/h
9c	:	Co-generation Unit with MP Steam Boiler:	37 Gcal/h

Figure 9
Energy Balance for Ammonia Urea Complex
(1350 MTPD Ammonia/2300 MTPD Urea)
Air Compressor on Gas Turbine Driver
Exhaust to Steam and Power Production

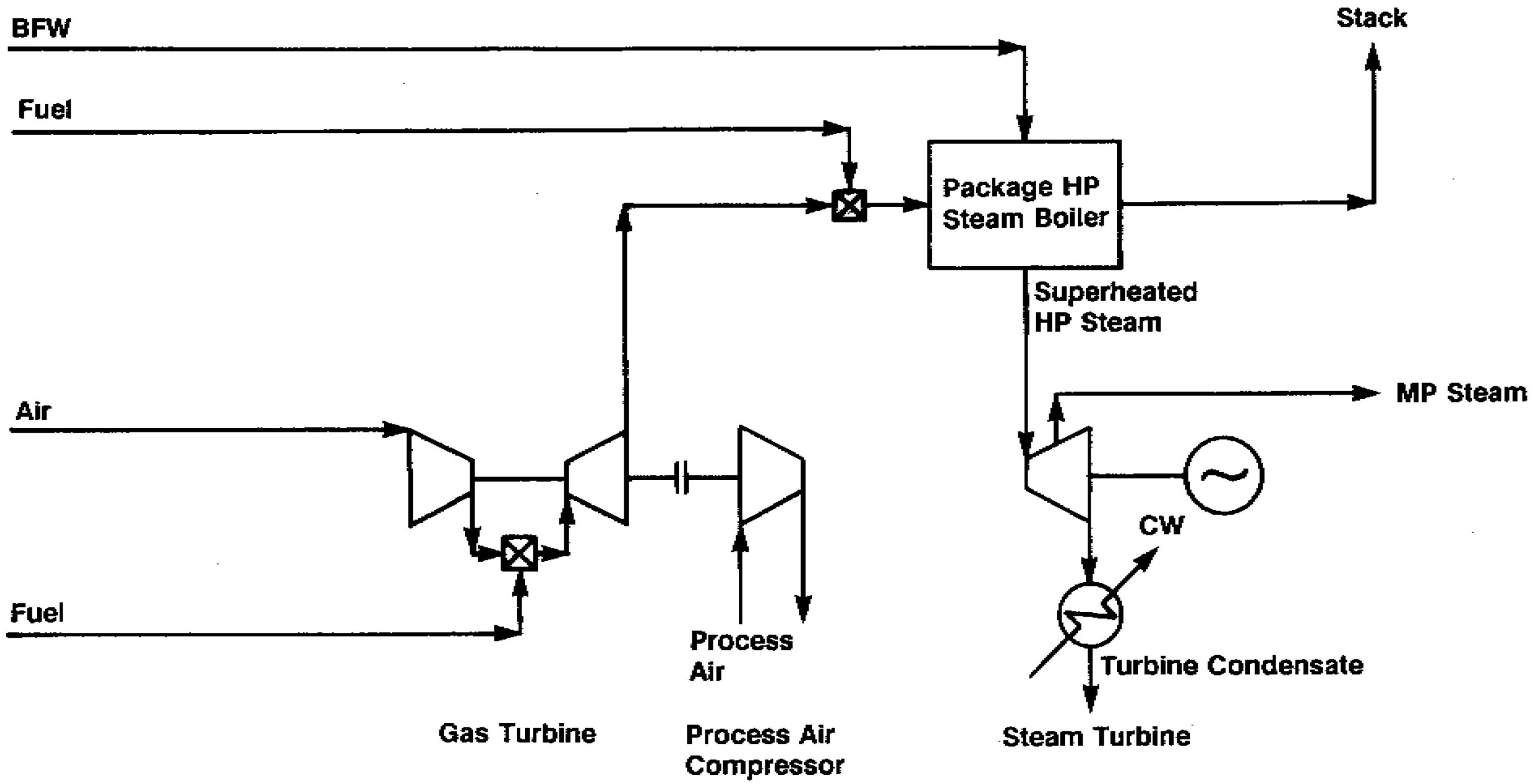


Figure 10
Integration of Gas Turbine Driver and
HP Steam Production with Turboalternator