# DESIGN OF FAIL-SAFE CONTROL SYSTEMS FOR STEAM REFORMING PLANTS

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When the Haber process for ammonia synthesis was first commercialized some 50 years ago, coal and coke were the raw material for most plants. About 25 years ago, the impact of natural gas as a raw material was first felt as a consequence of the commercialization of the steam-methane reforming process. This process for gas preparation has been refined and improved over the years and present indications are that steam reforming will be used for every ammonia plant currently in design or construction in the United States.

The technology by which synthetic ammonia is manufactured continues to evolve in a manner characteristic of a vital, expanding industry. It is pertinent that the dramatic reductions in ammonia plant investment and operating costs have been associated with advances in generation of synthesis gas rather than with radical improvements of the ammonia synthesis itself. For this reason, and because of the extreme conditions to which attendant equipment is subjected, this article is directed towards the generation of ammonia synthesis gas and specifically at discussion of safety considerations inherent in such plants for current operating conditions.

## Technological developments

The technological developments in the steam-methane reforming process, which account for its unanimous acceptance for new projects have been principally in the areas of higher operating pressures, higher operating temperatures, and larger capacity units. These changes were made in conjunction with the availability of new and improved materials of construction and as catalyst characteristics, both physical and chemical, have been improved.

Plants in design and construction in the United States today employ high pressure, steam-methane reforming, in the range of 300 to 500 lb./sq. in. gauge. Individual unit capacity has increased to 600 ton/day and larger. New design problems are introduced by size but, for the most part, the safety problems are the same problems which have always existed in smaller plants operating at lower pressure. Continuing effort by design engineers, aided by the experience of operating engineers, has resulted in a design practice which includes the usual safety features of sound process and mechanical design, but which also considers that mechanical failure is an ever-present possibility and which, therefore, provides that the hazard to personnel and property of such failures will be minimized.

## Typical flow sheet

In any new project, the first consideration of safety must be taken during the early stages of plant design. This may be shown with reference to Figure 1, which is the flow sheet for a typical steam-methane reformer for a 600 ton/day plant.

Desulfurized natural gas is used for feed and fuel. The portion used for feed is mixed with steam, preheated to 800 to 1,000°F in the convection section of the reformer furnace, and introduced into the top of the catalyst-filled tubes of the reforming furnace. The portion of the gas used for fuel is supplied to the burners at the top of the furnace radiant box.

Boiler feed water is pumped to a steam drum. Natural circulation is through a boiler coil in the convection section of the furnace. The steam generated in the coil flows from the steam drum and mixes with the preheated natural gas feed.

## Nickel catalyzed reactions

Steam and natural gas mixture flows downward through parallel furnace tubes, 300 to 500 in number. The internal pressure is 300 to 500 lb./sq. in. gauge. Firing of natural gas fuel serves to heat the steam-gas mixture. The catalyst, in which 20 to 30% nickel is the active ingredient, promotes the reactions:

$$H_2O + CH_4 \longrightarrow 3H_2 + CO \qquad (1)$$

$$H_2O + CO \longrightarrow H_2 + CO_2 \qquad (2)$$

The gas at the catalyst tube exit is at approximately 1,400 to 1,500°F and contains substantial quantities of residual methane.

The secondary reformer is fed with hot gases from the primary reformer plus preheated air. These two streams are mixed and immediately enter a bed of reforming catalyst. The gas passes downward through the catalyst; the heat of oxidation of the partially reformed gas elevates the temperature to 1,700 to 1,800°F and supplies the energy to further the reforming reaction. The exit gas contains approximately one quarter of one percent methane.

## Catalyst tubes

The catalyst tubes are specified as centrifugally cast 25 Cr–20 Ni stainless steel; they are 3 to 5 in.

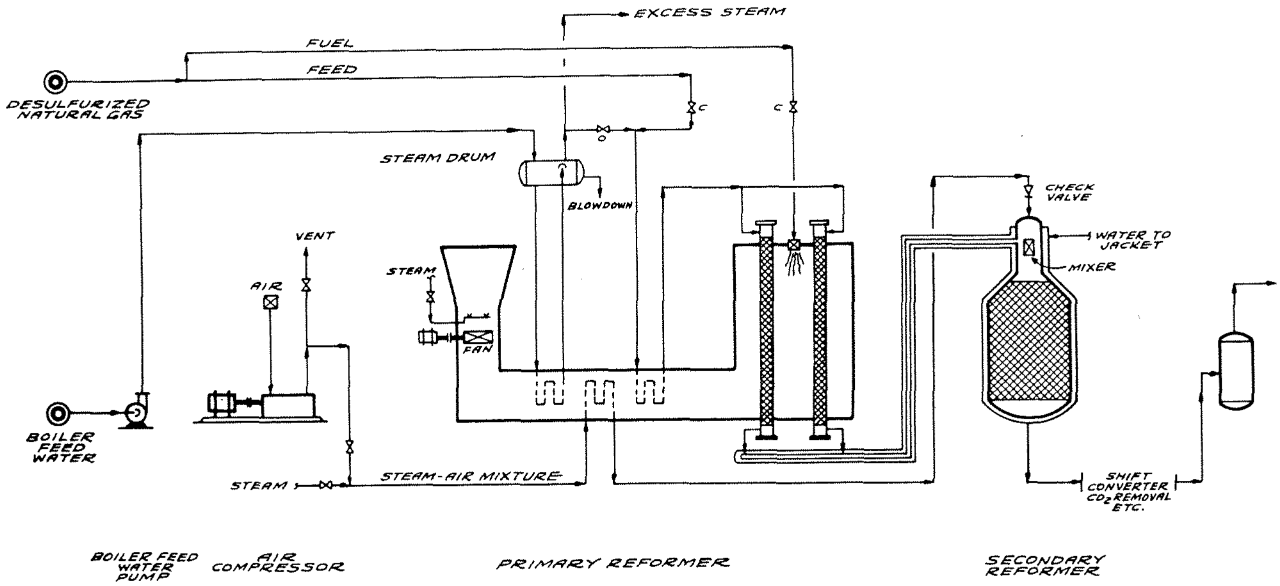


Figure 1. Flow sheet for a typical steam-methane reformer for a 600 ton/day plant.

I.D. and are approximately 1-in. thick. Tube metal temperatures are calculated to be 1,600 to 1,650°F on an end-of-run basis. For design, a safety factor equivalent to 50 to 70°F is taken, part of which provides for statistical fluctuations in temperature distribution. Tubes are accepted for use only after passing rigid purchasing and inspection requirements.

Gas from the primary reformer flows to the secondary reformer via the transfer line. Recent designs employ an internally insulated carbon steel line, positioned in an open water bath. Adoption of this type design eliminates potential problems with alloys in the temperature range encountered. Furthermore, expansion problems are reduced permitting a short, straight run of pipe between primary and secondary reformers. Insulation failure, if it should occur, will cause easily noticed boiling in the water bath without creating the hazard of pressure wall failure due to overheating.

## Air compressors

The air compressor is required to deliver air to the secondary reformer at pressures of 300 to 500 lb./sq. in. This is not an extreme or unusual condition for air compression, but it is important to design a system which will avoid the hazard of explosion due to lubricant decomposition. In large plants this problem is easily avoided as centrifugal or rotary air compression is generally selected for economic reasons. For smaller plants, say 300 ton and smaller, it is considered good practice to limit compression ratios so that discharge temperature will be approximately 300°F or lower at the high pressure stages and approximately 350°F or lower at the low pressure stages. Synthetic lubricants could be used to permit higher discharge temperatures but this has not been found necessary or desirable in ammonia plant design.

The secondary reformer is a carbon steel vessel, internally insulated with castable material and protected by an open water bath. This design, similar in principle to that employed for the transfer line, minimizes the likelihood of overheating, and provides a safe warning in the event insulation failure should occur. The potential hazard, in this regard, has risen sharply as the pressure has increased. It is not that the likelihood of lining failure has increased, in fact, with improved casting methods, the reliability of the insulation has been improved. The operating conditions require an internal insulation and the short time strength of the pressure shell is insufficient for full exposure to flow temperature.

## Reflecting potential extremes

The design conditions for the secondary reformer must reflect the potential extremes of temperature and pressure which may occur. The normal operating temperature is approximately 1,800°F; however, at the mixer and at the top of the catalyst bed, the possibility exists that the theoretical flame temperature, approximately 2,300°F, may be approached. While the normal operating pressure is 300 to 500 lb./sq. in. gauge, the design of the secondary reformer (plus associated equipment) must consider the possibility of explosion pressures occurring.

This brief description of the typical steam-methane reformer has permitted one to touch briefly on several of the safety considerations which must be taken in the early stages of process and mechanical design. In summary, the major considerations are:

1. Safe design of reformer tubes
2. Safe design of transfer line
3. Safe design of air compression systems
4. Safe design of secondary reformer

## Instrumentation required

Having, thus, briefly described the flow sheet for a typical steam reformer, one can now consider the instrumentation required. Instrumentation is expected to perform the following functions:

1. Regulate the various independent process variables at or near their design values, and certainly within their safe ranges, as determined by the process and mechanical design.

2. To react in a safe manner in event of failure of process equipment, including failure of the instruments themselves.

The instrumentation required for the regulation function are relatively simple and few in number. There are several different ways in which the basic regulating instrumentation can be set up, but for the typical flow sheet the following is suggested:

1. The rate of flow of feed gas, reforming steam, and air is measured and regulated, using flowmeters, automatic controllers, and control valves.
2. The pressure of the entire system is measured, and is controlled by a suitable system at the synthesis gas compressor.
3. The rate of flow of fuel gas is regulated manually on the basis of measurement of residual hydrocarbon at the outlet of the secondary reformer—so long as certain critical temperatures are not exceeded.
4. Suitable boiler controls will be required. These will be in accordance with applicable code requirements.

## Supplemental data

In addition to this bare minimum of measuring and regulating instrumentation, it is generally considered good practice to provide supplemental data, for example:

1. Temperature of preheated air, gas, and steam.
2. Temperature of primary reformer banks.
3. Temperatures at the secondary reformer.
4. Gas analyses at effluent of primary and secondary reformers.
5. Transfer line temperatures.
6. Indication of furnace draft conditions.
7. Furnace convection temperatures.
8. Compressor controls.

The above instrumentation, very simple in concept, constitutes all of the control requirements for normal regulating functions. Now, having briefly outlined the safety factors designed into the equipment and the minimum instrumentation needed to insure operation within the limitations of these designs, it is necessary to examine the interrelationship between equipment and instruments to prevent impending failures and to determine action required so that any actual failures occur in a safe manner. The remainder of this article will be devoted to this design aspect.

## Conceptual approach

The approach to this subject is conceptual; that is, a discussion of the means available to maintain plant safety without detailed consideration of specific instruments or controls. Recognition is given immediately that the situations described may be instrumented for safety in a different fashion than that noted. Specifically, in computer-controlled plants, the specific instruments and the control circuits will vary from those in plants using conventional pneumatic or electronic instrumentation.

As a general rule, it is not necessary to consider the simultaneous occurrence of two unrelated failures in series or in parallel for this service. Such double contingency is, of course, an extremely remote possibility and the costs of the instrumentation required to protect against a double contingency is not justified.

One can now discuss various failures which may occur, the consequences of such failures, and the precautions taken to make, as far as possible, each such failure a safe one.

## Feed failure

Failure of feed may occur in one of several ways, for example, failure of a feed gas compressor, inadvertent closing of a valve, etc.

If the feed is lost totally, the resultant hazard is that oxygen will not be consumed at the secondary reformer, will flow through the process, and may mix with combustible gases in downstream equipment. Further, flow of oxygen onto activated catalyst will lead to uncontrolled oxidation of the catalyst with destruction of the catalyst and danger of failure of the containing vessels.

If feed loss is partial, the ratio of air to combustibles at the secondary reformer will rise, causing a significant and potentially dangerous rise in temperature at the secondary reformer.

This contingency can be safely handled by temperature alarm at the secondary reformer coupled with instrumentation designed to provide for rapid cut-out of air to the secondary reformer.

## Steam failure

It is good design practice to set up the steam system, insofar as possible, so that any foreseeable sudden steam demand by other steam users will not allow supply of steam to those users at the expense of the primary reformer.

Even after such precautions are taken, it is, of course, still possible that the supply of steam to the primary reformer can fail, for example, by failure of boiler controls.

Failure of steam to the primary reformer may cause immediate damage to the primary reformer; carbon deposition will almost certainly cause catalyst damage; resultant local overheating could conceivably cause a tube failure. Similarly, temperatures will rise in downstream equipment. This occurrence is not likely to be a serious hazard, but is, nevertheless, to be avoided if possible. It is important that feed gas be cut off immediately, and that air and fuel be cut out next.

It has become the practice to link the controllers for feed and steam by means of ratio measurement and alarm. Should the steam to carbon ratio fall below a predetermined critical value, both the feed to the primary reformer and the air to the secondary reformer will be cut off automatically.

It is to be noted that, if the previously mentioned instrumentation in regard to feed failure is employed, the loss, or reduction, of feed flow will result in cut-off of the flow of air to the secondary reformer.

## Automatic stoppage of fuel

At this point, it is in order to consider the possibility of providing instrumentation to trip out fuel automatically, following a steam or feed failure. This consideration is generally rejected, on the grounds that a complete shut-off of fuel is likely to permit the furnace to cool rapidly, particularly if any flow of steam continues through the tubes. Extinguishing the fires in a hot box can create an extremely dangerous condition, in event any minor leaks occur.

It is practice, in view of this, to arrange instrumentation so that fuel will not be cut out automatically. Instead, controls are purposely kept manual and are arranged so that the operator can quickly and easily adjust fuel flow. There is one exception to this, discussed later under "draft failure."

## Air failure

Failure of air to the secondary reformer may occur in several ways, the most likely of which is a trip-out of the air compressor.

Air compressor failure will create an immediate hazard if hot combustible gas in the secondary reformer is allowed to flow backward into the air line. A check valve is usually provided, located near the secondary reformer. However, one should not rely on the check valve for complete protection. In addition to the check valve, new designs include continuous steam flow in the air line, valves to block the air line downstream of the compressor, and means to admit additional steam in large quantity downstream of the block valve.

## Draft failure

In an induced draft or forced draft furnace, draft failure can occur by fan failure. Draft failure will create hazardous conditions because of the tendency of the down-fired flames to escape upward from the radiant box.

It is practice to provide steam rings, with automatic cut-in in event of fan failure. The steam rings are designed to create a draft in the furnace stack which is designed to provide a Venturi effect.

In some plants, it is judged that the large, sudden steam demand created by cut-in of the steam ring will create further problems. In this case, automatic fuel cut-off is used as an alternative safety measure. As mentioned above, one considers fuel cut-off poor practice, and this is the only instance in which it has been used (aside from instrument air failure).

## Instrument air failure

Instrument air failure can occur locally or in an entire system. For the present, one shall consider total air failure; local failure will be considered below when one considers failure of individual controllers.

Valves can be selected to open, close, or remain stationary in event of instrument air failure. The choice must be made carefully, considering not only the individual circuit but the entire process, including the action of all other valves.

Referring to the instrumented simplified flow sheet, Figure 2, air failure action recommended is as follows:

| | |
|---|---|
| Feed gas control valve | Close |
| Steam control valve | Open |
| Air control valve | Open (stop air to process) |
| Fuel control valve | Close |

## Controller failure

Provision can be made to assure a safe action in event of controller failure. It is assumed, when considering controller failure, that the sensing instrument is functioning.

In the case of the feed gas controller, a failure causing loss of feed will react, as with any other cause of feed failure, to cut off the air compressor. A failure causing an increase of feed is not likely to be hazardous.

A failure of the steam controller causing loss of steam will bring about an orderly shutdown with the instrumentation provided. A failure causing an increase in flow is not likely to be hazardous.

A failure of the air controller causing a loss of air will activate the quick acting valves to shut off the air line and inject steam. As illustrated, instrumenta-

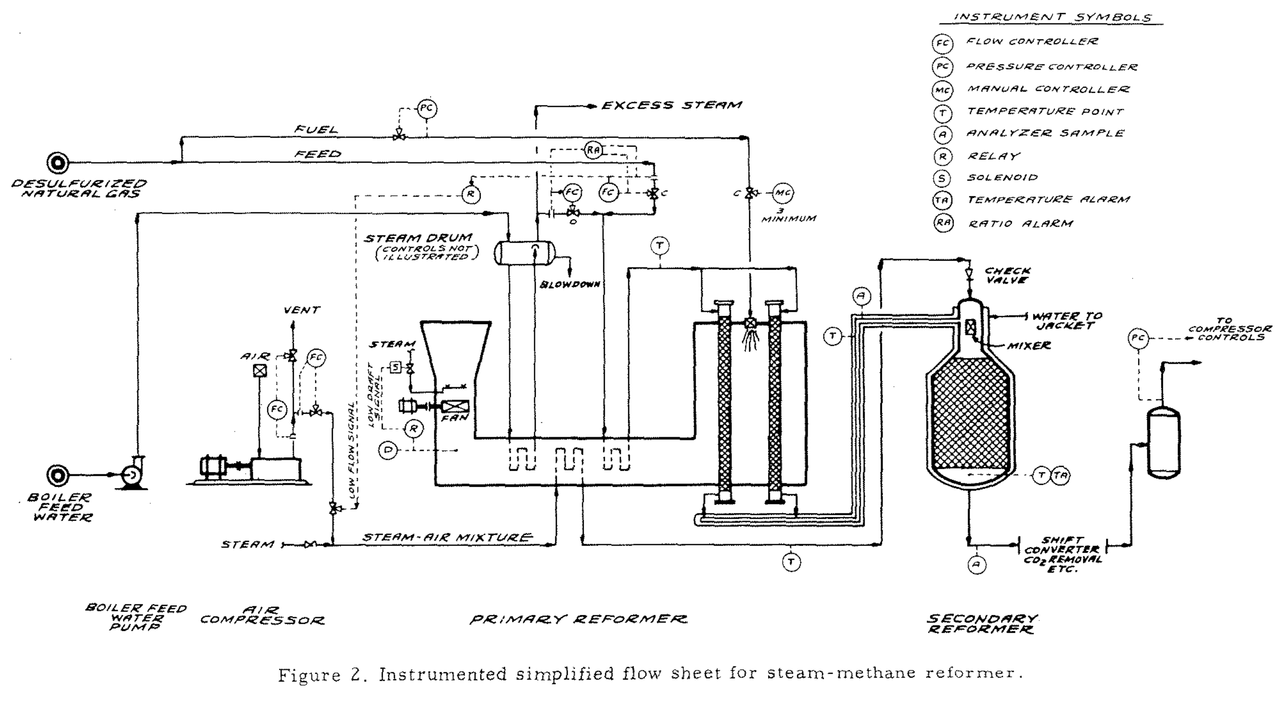


Figure 2. Instrumented simplified flow sheet for steam-methane reformer.

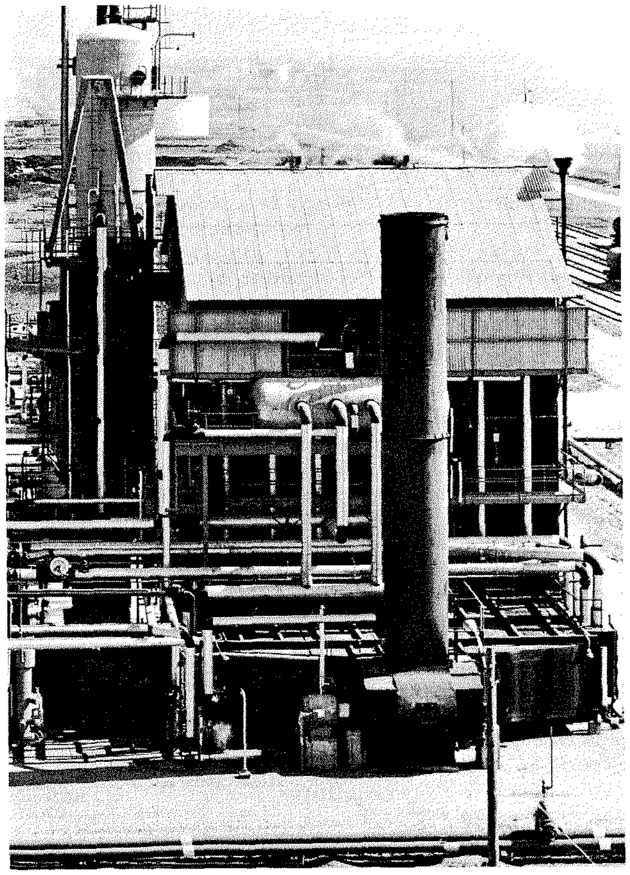

Figure 3. Primary reforming furnace and secondary reformer for 600 ton/day ammonia plant at Texas City, Texas.

tion may be extended to shut down the compressor in this instance.

A failure causing an excess of air flow will result in hazardous overheating at the secondary reformer. This contingency can be accommodated by instrumentation arranged to signal for compressor shutdown when secondary reformer temperature reaches a predetermined level.

In one type design, multiple controllers for fuel gas are used in parallel; the minimum number in reforming furnaces is three. Therefore, failure causing a loss of flow in any single supply is not hazardous. A failure causing an excess of flow will not be particularly hazardous, and will be easily noticed by the furnace operator.

## Sensing instrument failure

In the following discussion, consideration is given to the problem of failure of flow elements, thermocouples, and pressure taps, as considered separately from the controllers.

Failure of sensing instruments creates a situation not easily handled by conventional instrumentation, short of installation of duplicate systems. Even this precaution is not likely to be foolproof; for example, if one steam meter freezes, it seems likely that two might freeze as well.

The sensing instruments providing information to the principal controllers are the feed flowmeter, the steam flowmeter and the air flowmeter. Failure of any one of these or failure of instrument air or power to an individual transmitter will create a characteristic set of symptoms as follows:

| Instrument Indication | Too low | Too high |
|---|---|---|
| Feed flowmeter | Low primary temp.<br>Low secondary temp.<br>High primary $CH_4$ | High primary temp.<br>High secondary temp.<br>Low primary $CH_4$ |
| Steam flowmeter | Low primary temp.<br>Low secondary temp.<br>Little change in primary $CH_4$ | High primary temp.<br>High secondary temp.<br>Little change in primary $CH_4$ |
| Air flowmeter | No change in primary temp.<br>High secondary temp.<br>No change in primary $CH_4$ | No change in primary temp.<br>Low secondary temp.<br>No change in primary $CH_4$ |

## Potentially dangerous temperatures

In regard to the sensing instruments which transmit signals to controllers, hazardous conditions can result if the indication from the feed flowmeter and the steam flowmeter are too high, or if the indication from the air flowmeter is too low. These are the conditions which will result in high and potentially dangerous temperatures. The instrumentation is designed to protect the system by warning of this condition. Operator reaction will consist of air shut-off or reduction of primary reformer firing.

The other critical sensing instruments are:

1. temperature of preheated steam-gas mixture
2. temperature of preheated air

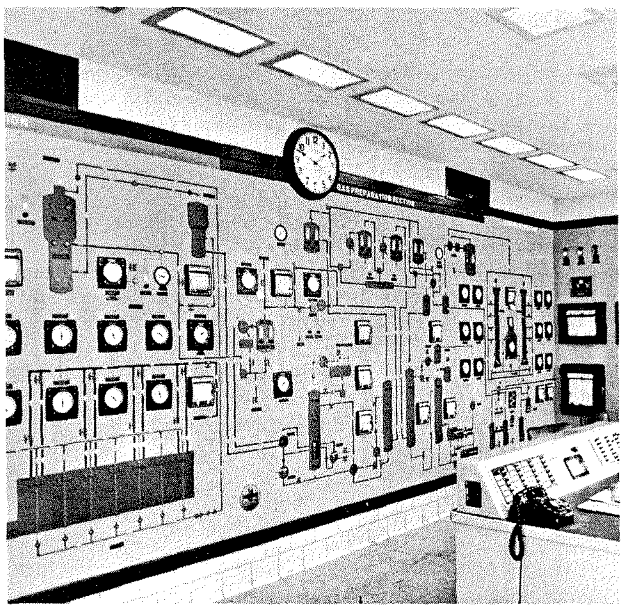

Figure 4. Control panel for 300 ton/day ammonia facility at the Solar Nitrogen Chemicals plant in Joplin, Mo., provides all of the data needed to maintain operation within design limitations.

3. temperature at primary reformer

4. temperature at secondary reformer

5. methane analysis at primary reformer

6. methane analysis at secondary reformer

## Thermocouple failure

In regard to the sensing instruments listed above, failure of thermocouples is probably the most common instrument failure. It is considered good practice to employ duplicate instrumentation at the secondary reformer which is the most critical service. These are separate thermocouples, in separate thermowells, distributed along the system to provide continuous monitoring in event of failure of a single point. The hazardous condition occurs if an instrument failure results in a reading which is too low. Frequent cross-checking by the operator, or an alarm system activated by any of the instruments, is satisfactory protection since reliability of alarm systems is usually high.

Failure of methane analyzers is not likely to result in any hazard.

## Boiler feed water supply failure

Loss of boiler feed water supply leading to loss of steam will disrupt the plant operation and can give rise to potentially hazardous situations.

The first step is to take all practical measures to insure continuous supply of boiler feed water. This will include a parallel pumping arrangement with automatic start-up of the spare pump. The second step is to supply sufficient reserve of water in or ahead of the system to provide for an orderly shutdown of the plant, thus, localizing the danger to that of overheating of the generation system through loss of water while still absorbing residual heat from equipment.

Low level in the steam drum and low flow in the supply will be signalled at the control board. As noted previously, reduction of process steam will initiate shutdown of the reforming section with automatic or push-button shut-off of air to the secondary reformer reducing temperatures from that point downstream. Reduction of firing is also done at the board and with proper sizing of the system, the situation is safely handled through natural circulation in the steam generation system.

## Suggestions for the future

This discussion has been restricted to pressure steam reforming and detailed consideration has been given only to a conceptual design of the safety aspects of instrumentation for this portion of the ammonia plant. By describing briefly some of the other design considerations, one is suggesting that the safety aspects of design of specific pieces of equipment may be themes for further discussion. This thought applies, of course, to the other sections of the plant as well as to the reforming sections.

Through the efforts of the A.I.Ch.E. Air and Ammonia Subcommittee, interest has been aroused and a positive contribution has been made towards improvement of safety in design and operation. It is suggested, however, that this Committee consider, as an extension of its responsibilities, a start on the codification of safety requirements leading to a consistent and higher degree of safety in design and operation—perhaps starting initially with ammonia plants, but planned to eventually include the entire fertilizer operation.

# DISCUSSION

ELLIS—DuPont: With the increased pressures in the primary reformer tubes, do you anticipate increased hazards in the reforming area as compared to present low pressure reformer tubes?

AXELROD: From the standpoint of our good experience and the continuing improvement of materials, a negative answer is indicated. The unit stresses employed in the design of high pressure reformer tubes are in the same range as in the old low pressure units.

WALTON—SunOlin: We've had a number of reports here at previous times of failures of 25/20 transfer lines and tubes in much lower pressures. Is 25/20 the only alloy that is suitable in strength for tube material for these higher pressure reformers?

AXELROD: Generally, I wouldn't say that; the choice is largely economical.

WALTON: Is Incoloy 800 a satisfactory material for tubes for these higher pressures?

AXELROD: I'm going to refer you to metallurgist.

SORELL—M. W. Kellogg: First of all, Incoloy is of course acceptable; however, it is not as strong as cast 25 Cr-20 Ni, especially the high carbon grades. Whether or not Incoloy offers a practical choice depends upon the size of the furnace tubes and on pressure and temperature conditions. The high pressure units now being designed demand exceptional strength properties and, therefore, dictate the use of strong, heat-resistant cast alloys such as HK-40. As Mr. Axelrod pointed out, our recent experience has been primarily with cast 25 Cr-20 Ni tubes.