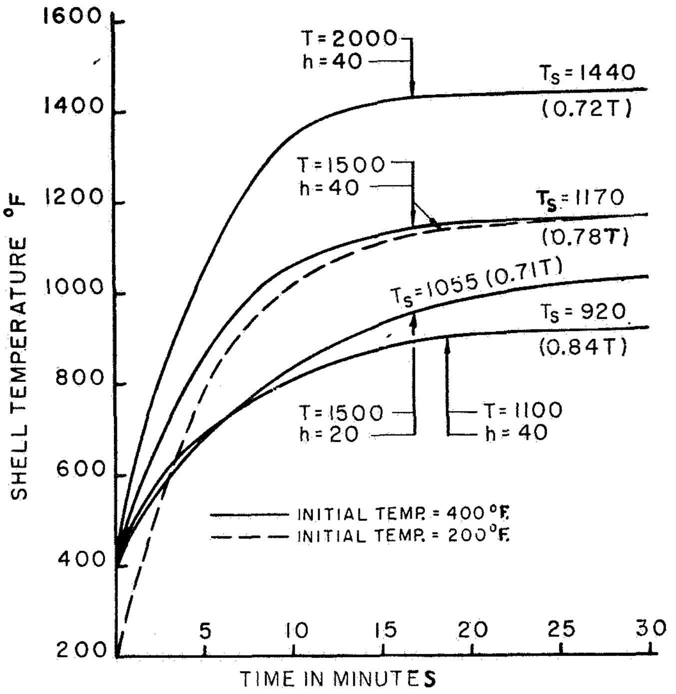

T = INSIDE FLUID TEMPERATURE, °F.
T_s = FINAL METAL TEMPERATURE, °F.
h = ASSUMED INSIDE FILM COEFFICIENT, BTU/(SQ.FT.)(HR.)(°F.)
AMBIENT CONDITIONS = 100°F. AIR AND NO WIND

Figure 1. Potential shell temperature at overheated zone for 1 in. metal thickness.

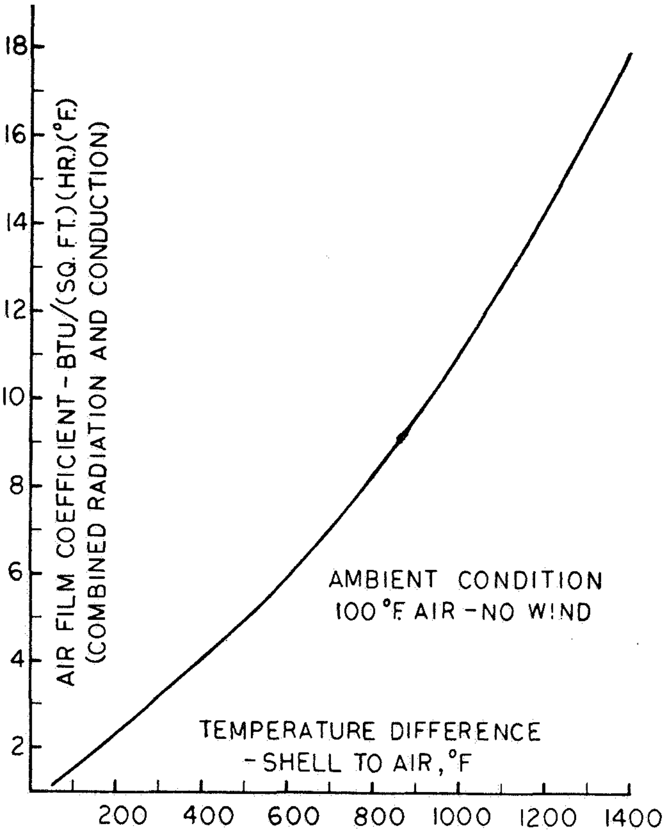

Figure 2. Air film coefficient.

A Re-evaluation Of External Water Jackets

Fifteen years ago it was believed that external water jackets would enhance overall safety, and improve initial and continued thermal performance on high temperature pressure equipment. Time and experience have confirmed that belief.

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THE USE OF INTERNALLY INSULATED PRESSURE VESSELS and piping components in high and moderately high temperature process plants is widespread. Their role has been increasingly important in making practical new combinations of pressure, temperature, and size. In addition to the careful attention which must be given to the choice and installation of the lining, even greater consideration must be given to control of the shell metal temperature, particularly with respect to avoiding temperatures which would cause shell rupture. A paper published in 1959 (*1*) presented a general discussion of pressure vessel overtemperature hazards and how they relate to internally insulated vessels. The advantages of external atmospheric water jackets for positive metal temperature control were outlined and successful usage was cited. Now, after ten years additional experience with over 90 installations by M. W. Kellogg Co., it is timely that the advantages of these jackets be re-examined.

Advantages of water jackets

The advantages of external atmospheric water jackets are:

1. The shell temperature is maintained very close to the saturated steam temperature, even under abnormal heat input much greater than design. This follows from the fact that the boiling water heat transfer film coefficient is very high (over 2,000 Btu/(sq.ft.) (hr.) (°F)) in comparison with the internal fluid film coefficient likely to be experienced under any condition.

2. Gas by-passing at the shell-insulation interface remains restricted and there is no accelerated spreading of the heated area in the event that there is either a flow of hot gas past a small portion of the shell, or a localized high heat input for any other reason. Since there is no significant increase in metal temperature, there is no local distortion to cause more heating and, in turn, more distortion.

3. Variations in shell metal temperature around the periphery and along the length are negligible; hence, there are no resulting distortions. The risk of initiating hot gas flow to the shell is minimized. With air cooling, substantial variations in shell temperature are to be expected even with the insulation in perfect condition.

4. The low metal temperature of the jacketed vessel is a favorable design condition for avoiding a gap at

the shell-insulation interface. Attainment of the same temperature with similar insulation and air cooling requires a thicker lining and larger pressure shell at an increased cost not justified by heat loss considerations.

5. System design for thermal expansion is made simpler and more assuredly predictable. Metal temperatures run dependably lower than with air cooling, while thermal strains on attachments and abnormal hot zones due to non-uniform circumferential temperatures, are prevented.

6. Where metal deterioration might occur at higher than normal temperatures that are not serious otherwise, jackets may insure the desired control.

The capability for positive control of metal temperature, advantage 1, must be regarded as the primary advantage since it offers the desired safety protection against rupture.

Prevention of radial shell growth and local distortion, advantage 2, is inherent in advantage 1 and, is itself, an equally important safety feature. Should active by-pass gas flow between the lining and the shell (the most common abnormality), the by-pass flow quantity and attendant potential heat release will be limited. In the absence of the jacket and with only air cooling, the shell would expand away from the insulation, the flow gap and flow quantity would increase in progressive steps, and the shell temperature would rise rapidly. A satisfactory installation must not only have safety provisions against rupture, but must perform adequately in plant operation. Advantage 2 is markedly superior to air cooling in providing greater assurance of attaining and maintaining design performance.

Uniform temperature, advantage 3, is generally helpful to lining performance since local temperature differences may cause local lining cracks or radial gaps, and initiate active flow behind the lining or lining deterioration.

With respect to advantage 4, the goal of keeping the lining in intimate contact with the shell is commonly recognized. Whether a gap will exist with castable linings depends on the differential expansion between lining and shell and on the initial lining shrinkage on setting and heating (*2*, *3*).

Advantage 5 is of interest primarily from a system design standpoint. For some applications the reduced and controlled metal temperature of a jacketed design may be the difference in making a particular system geometry practical. Distortion control is of interest from a maintenance standpoint. With un-jacketed construction, non-uniform circumferential temperatures can result from weather conditions as well as variations or changes in lining performance.

To bring out more sharply the different capability of water jacket vs. air cooling under abnormal local heat input conditions, Figure 1 has been prepared as an illustration of the temperature-time history of shell metal at the center of a hot spot on an air cooled shell. Air has been assumed to be at 100°F and still, and an external film coefficient, as shown in Figure 2, has been used. The "spot" is assumed to be large enough so that edge effects can be ignored. The shell is considered to be operating at a normal temperature of 400°F, and then suddenly exposed to active gas flow at assumed temperatures of 1,100°F, 1,500°F, and 2,000°F due to loss of insulation or by-passing behind the insulation. Constant internal gas film coefficient and gas flow temperature have been assumed. The temperature of the spot has been plotted as a function of time after exposure for an assumed metal thickness of 1 in. Under these conditions, dangerous temperatures can be reached in a matter of minutes.

One curve has been included for an initial temperature of 200°F instead of 400°F, and it shows no significant change in the time required to reach maximum temperature.

Since the rate of temperature change is inversely proportional to the thickness, the time required for metal of any thickness other than 1 in. to reach a given temperature may be obtained by multiplying the chart time value by the thickness.

For the assumed conditions, final temperatures are in the range of 70% to 84% of flow temperature. An actual case would have to consider the quantity and heat capacity of the abnormal flow such as cited in reference (*2*). Nevertheless, despite the simple assumptions, the maximum temperatures indicated are not out of line with actual experience. For the same assumptions of abnormal temperature and gas film coefficient at the inside surface of a pressure shell protected by an atmospheric water jacket, the resulting heat flux through the metal wall is in the range of 25,000 to 70,000 Btu/(sq.ft.) (hr.). This is well below the critical flux required to cause film boiling. Therefore, assuming that an adequate supply of water of the proper quality is provided to the heated surface, no significant temperature rise should result.

Although water jackets are able to compensate for deficiencies in lining design or installation it must be emphasized that this is not the intent. They are supposed to promote safety and to increase lining reliability; hence, there should be no relaxation in the care given to design and construction of the lining. The latter is not within the scope of this article, but it has been thoroughly discussed in other papers (*2-6*).

Objections to water jackets

The most frequently stated objections to water jackets are:

1. The jacket prevents direct viewing of the shell.
2. Thermal performance of the lining can be judged only by jacket boiling pattern or measurement of water boil-off rate.
3. A small area zone of local increased heat input is not likely to be detected.
4. When increased steam rate is detected, the location of the increased heat input zone is not readily determined.
5. The jacket water may cause external corrosion of the shell.

The first four objections are commonly cited and must be carefully weighed against the advantages. For example, the objection that a small area of abnormal heat input is not likely to be detected is offset by the reduced probability of the incidence of such areas. So long as it is possible to detect deterioration well below tolerable limits by changes in the boiling pattern or water boil-off rate, inability to detect smaller amounts of local deterioration should not pose a safety problem.

When lining performance deterioration is noted, its cause must be ascertained by internal inspection. Stainless shrouded insulation poses a problem in this regard. Inspection measures include drilling and probing, or radiography with cut-outs made at suspect areas. Similar shut-down maintenance inspection will generally provide earlier warning of deterioration or potential problem zones. External inspection of the shell during shut-down can be facilitated by providing bolted or welded hand-hole type openings for inspection with mirrors or similar means. These are not provided as a design feature, but they can be added easily by operating companies. Cutting out a jacket section for closer inspection or work on a specific zone poses no great problem.

External pitting or stress corrosion of the shell can be controlled by control of the water quality used. Also, jackets are provided with covers to minimize possible contamination by atmospheric dusts. Possible condensate corrosion on the inside of the shell requires consideration in the design stage for both jacketed and bare shell design. This has not proven to be a problem in jacketed vessels to date as far as we know.

Discussion and evaluation

The advantages expected from the use of water jackets, together with the objections to their use, were carefully considered by M. W. Kellogg approximately 15 years ago. Safety considerations were paramount and emphasis was placed on providing maximum protection against shell rupture due to overheating. The decision was reached to make jacketed construction the standard choice for high temperature service in situations where overheating would create the risk of rupture in a very short time. The basic reasons for this decision were the advantage of a very high boiling film coefficient and the derivative advantages of controlled, lower, more uniform metal temperatures, and the practical elimination of any tendency of a small area of high local heat input to be self enlarging. It was recognized that the choice was not ideal, but it was judged that the objections to water jackets were outweighed by the potential rapid acceleration of a hot spot, the major safety disadvantage of bare shell operation. With a water jacket, significant malfunction of the lining should be detectable through increased steaming and water make-up rates while metal temperatures are practically unchanged. Thus, detection and safe shut-down are possible with metal temperatures maintained at safe operating levels.

As a guide in applying this decision, we used the criterion suggested by Rossheim et al (*1*) for shells having no external insulation, viz., jackets to be used where the shell stress due to internal pressure would exceed the 1,000 hr. rupture strength at a metal temperature (°F) equal to 80% of the internal fluid temperature. This, of course, assumes that the resulting normal shell temperature is satisfactory for the service conditions. As with any rule of thumb, specific cases may warrant individual consideration.

While this policy was based upon safety considerations, it was recognized that the advantages of lower and more uniform temperatures and the avoidance of a gap between the lining and the shell made conditions decidedly more favorable toward assuring design thermal performance of a refractory castable lining both initially, and during its service life.

The decision was the immediate result of an analysis of service experience with a secondary reformer on an ammonia unit and five identical vessels in similar reforming service at higher pressure on another unit. Despite previous satisfactory experience of about 14 years in the use of internal insulation in process pressure vessels and piping in hydroforming, reforming, and fluid catalytic cracking service, all six vessels developed hot shell zones shortly after being placed in service. The problems and the care required for the design and installation of effective linings were well known and utmost care had been given to these procedures on these vessels.

In the case of the single secondary reformer, the overheated area originated at the brick support which penetrated to the shell and it was suspected that the concrete castable had a void at this zone. There was no evident deficiency in the linings of the other five vessels; hot zones in these occurred only as unit throughput was raised and were very clearly responsive to this factor and associated bed pressure drop. Increase in flow would widen the area of an overheated zone and might initiate a new zone. By-pass flow of gas between insulation and shell was clearly indicated.

Sectional water jackets were installed on the shell of the five vessels over the catalyst bed zone of high pressure drop. The water in the jackets only simmered, indicating stabilization of lining performance at intended design and demonstrating the advantage of the low uniform temperature in keeping the insulation and shell in firm contact and preventing gas by-passing (advantage 2). A few months later one of these vessels suddenly developed a local hot area in the upper unjacketed conical portion adjacent to nozzle penetrations where there was no catalyst bed. Although this was noticed visually and unit depressuring started immediately, a local bulge and a small rupture occurred before full depressuring was realized. Jacket protection was then extended to these zones.

In the case of the single secondary reformer, installation of a water jacket also controlled the shell temperature and permitted safe operation; the water surface indicated somewhat greater steam generation than normal design but not as much as might be expected from the prior temperature and area of the overheated zone.

Eventually, the linings were replaced on all six vessels at a convenient time. Some insulation void was found at the brick support crotch zone on the single secondary reformer but the only abnormalities found on the other five vessels were narrow circumferential bands of lower strength and probably increased porosity at the top of each sectional castable pour caused by segregation of fines and probably a higher water-cement ratio. These were not considered to explain the observed performance. The service of these vessels, after jacketing, has been quite satis-

Table 1. High temperature jacketed vessel and exchanger service experience.

Vessel Service	No. of Vessels	Range			Service Years	Service Vessel Years	Catalyst Bed
		Press. psi	Temp. °F	Insul. I.D. in.			
Secondary Reformer	50	50 to 500	1,750 to 2,300	60 to 129	1 to 14	260	Yes
Heat Exchanger	44	300 to 500	1,100 to 1,825	46	1 to 5	110	No

factory and is included in Table 1.

It is interesting to note that Huggett (*2*), after detailed consideration of ICI (Imperial Chemical Industries, Ltd.) experience and study of the overheating potentials, concludes that a water jacket is the only certain answer to the problem of minimizing the possibility of gap formation between lining and shell and consequent overheating. He reports that secondary reformers on all ICI designed plants have water jackets and have been completely successful. James (*7*) and Kratsios and Long (*4*) also cite the safety problem posed by the potential accelerating temperature rise at a local hot spot caused by radial shell growth in air cooled construction.

Jacket arrangement and water supply

To attain and maintain the safety and other advantages of water jackets, it is essential that they be full of water and provided with an adequate water supply at all times while in operation. The supply, arrangement, instrumentation and operational checks should be suitable for this objective and provide ample warning of loss of level, or supply, for corrective steps or safe shutdown.

Vessel jackets, as used by the M. W. Kellogg Co., have consisted of either sectional or one piece open-top annular ring troughs several inches wide. Initially, sectional type secondary reformers were used with water feed going to the top section and with other sections fed by the overflow from the section above. If abnormal heating occurred, the area could be localized to the individual section. We are not aware of any instance of overheating so that this maintenance advantage did not come into play. Later designs are of the one piece type, which simplifies the number of level and feed control points, as well as the cover and vent arrangement.

Figure 3 shows a typical arrangement for the jacket of a waste heat boiler. Jacket level is maintained at the overflow pipe. Assurance against loss of water level is obtained by maintaining ample excess flow beyond make-up requirements. Excess flow is checked by regular operational observation of overflow discharge and a glass gage for visual inspection of the water level is also provided. A low level alarm is provided to warn of initiation of loss of level. A few installations have been made without constant overflow using automatic level control operating on feed. In addition to the normal cooling water supply, a second emergency source is provided.

Jacketing of internally insulated piping is similarly arranged. On horizontal lines jackets are "U" shaped with flat covers. Figure 4, (*8*), illustrates lining and jacket construction at a riser connection to the horizontal transfer line.

The design of jacketed construction includes a check of the metal temperature of the shell with the internal lining assumed to be performing per design, but with no water in the jacket in order to assure that the yield strength of the material is not exceeded. When empty of water, the jacket acts as an insulator and reduces the external heat loss. This effect is illustrated in Table 2, which gives the shell temperature with a dry jacket and the corresponding temperature of a shell with no jacket for two assumed values of insulation conductivity.

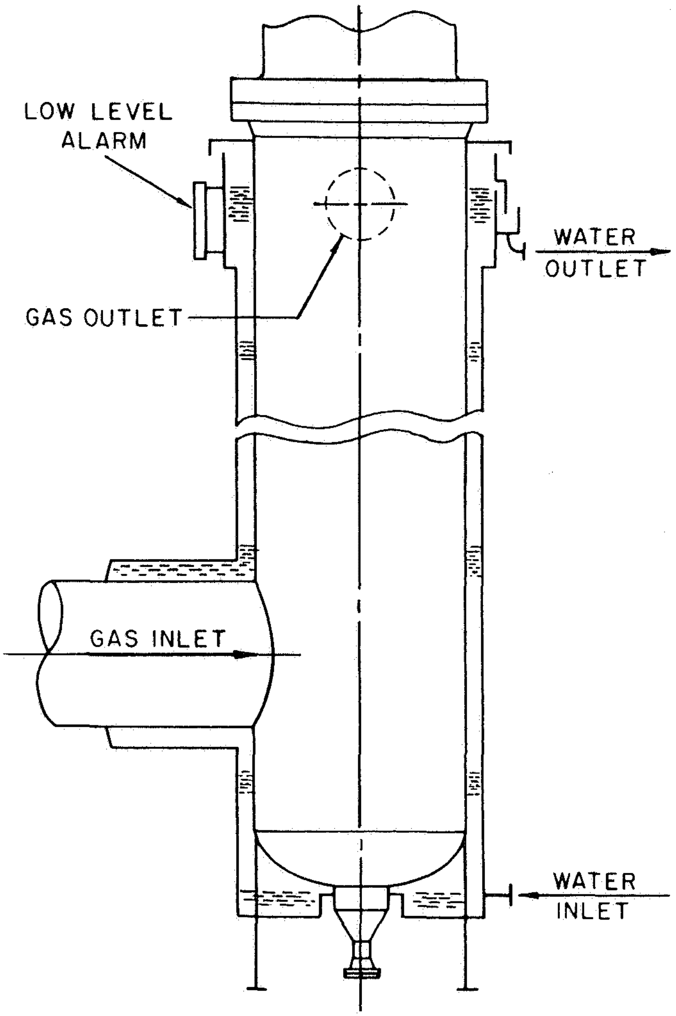

Figure 3. Typical water jacket for a waste heat boiler.

It should be emphasized, however, that this does not imply that one can afford risking loss of the jacket water since the increased shell expansion would be expected to open a gap between insulation and the shell and would also do away with protection against progressive enlargement of the gap in the event of local high heat input. With occurrence of hot gas bypass flow, the metal temperature would exceed the values in Table 2, and could exceed those of Figure 1. A permanent bulge could occur and could go undetected unless it led to penetration of the pressure shell.

Table 2. Comparison of temperature of shell having a dry jacket with that of an air cooled shell.

Internal Insulation		Temp., °F		Calc. Shell Temp., °F		Shell Temp.
t (in.)	k*	Inside (flow)	Air	No Jacket	Dry Jacket	Increase °F
4	7	1,800	100	550	720	170
4	1.3	1,800	100	295	400	105

**Conductivity Btu/(°F)(in.)(hr.)*

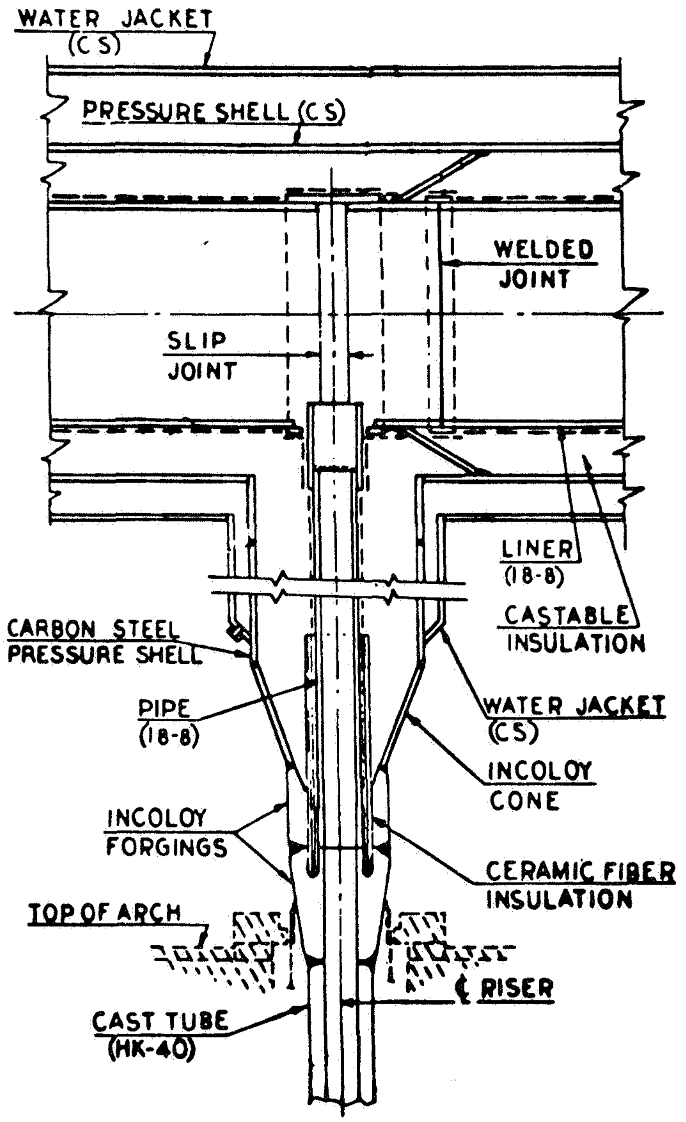

Figure 4. Jacket and lining detail at riser connection to transfer line.

The design of a water jacket system should provide for abnormal conditions, but it would be unreasonable to assume a complete loss of internal insulation. Rather, the system should have a heat removal capacity adequate to handle partial overall loss of effectiveness, or total loss of insulation at a local area of reasonable size. The capacity should provide an adequate margin above the minimum increase in heat loss which can be readily detected by operational monitoring. The assumed loss of lining effectiveness should be established considering the individual service and lining construction and applicable representative service experience. The assumed internal heat transfer film coefficient under such conditions should be consistent with the nature of the fluid and internal flow.

An analysis of boiling heat transfer is beyond the scope of this article, but summary treatments, together with extensive lists of references, are provided by Kreith (*9*) and McAdams (*10*).

The cooling capacity of a water jacket is largely dependent upon its size, flow rate, and the cleanliness of the pressure shell surface which, in turn, depends upon the quality of the cooling water. Maximum capacity is obtained by maintaining a sufficient flow of good quality water through the jacket to prevent high values of steam quality in the annular passages.

Service experience

M. W. Kellogg has accumulated considerable operating experience over the past 15 years with internally insulated pressure vessels equipped with external water jackets and operating at temperatures above 1,200°F for one year or more. The scope of this experience, acquired predominantly through handling the process gas on ammonia units, is illustrated by Table 1.

The higher temperature reformer vessels with a catalyst bed are internally insulated with a dense refractory concrete castable. Service with the water jackets has been uniformly good, although one secondary reformer unit did experience a local bulge and vertical rupture in the upper shell course after seven years of successful operation. The unit was started up in freezing weather without any water in the jacket, and it is this lack, rather than the lining, which evidenced no deficiency when it was removed for local shell repair, that caused the failure.

The 44 vertical heat exchangers of Table 1 are insulated with a castable insulation installed behind sectional stainless steel shrouds. Each cylindrical shroud has a cone at one end which is seal welded to the shell to prevent gas by-passing and protect the insulation from flow erosion. At the other end it has an overlap slip joint for axial differential expansion between shroud and shell. With the exception of the bubbled alumina installed on a few recent units, the installation has been a lightweight, low conductivity castable. More maintenance has been required on these exchangers than on the secondary reformers. The four cases we are aware of in which a rupture of the pressure shell has occurred due to overheating are discussed below.

Case 1: Bulging and a 6 in. vertical fracture occurred on the shell below an outlet nozzle. The nozzle liner penetration relative to the shroud conical seal was such that a gas by-passing path existed. It was found that a drain plug provided for initial jacket flushing had not been installed. Water feed and internal overflow pipes were arranged so as to prevent establishment of a water level that could be seen by the operators. Insulation was in place. Overheating was the result of gas by-passing and failure due to lack of water protection. Shroud details were corrected and jacket water provisions were modified to prevent future failure as well as provide a gage glass and low-level alarm for operational checking. Since these changes were made, the unit has operated successfully for 4½ years.

Case 2: Shroud details were initially the same as in Case 1, except that water levels had been properly established and maintained and no operational problem developed. As a result of information on Case 1, field modifications were made at a convenient time. Several years later bulging and a 6 in. vertical fracture occurred in the upper shell section. Client reported loss of water level occurred and condition of shroud seals could allow by-passing. Failure was ascribed to loss of water.

Cases 3 and 4: In the other two cases, failure of the pressure shell due to overheating was quite similar, but the precise causes of overheating were not conclusively established.

Ammonia unit transfer lines

In addition to the vessels and heat exchangers, we have worked with large ammonia unit transfer lines to and from the secondary reformer equipped with water jackets and with internal stainless steel shrouded insulation similar to that installed in the heat exchangers. About 30 units have been operating for more than one year, and some for as long as five years. Our experience here essentially parallels that of the heat exchangers. As far as we know, there have been three ruptures of the pressure shell in the line to the secondary reformer and one failure on an outlet transfer line. In addition, inspection while repairing an inlet transfer line disclosed a bulge and crack on the outlet transfer line.

Case 1: In this inlet line case, mentioned by Mayo (*10*), the shell showed a major diametral increase at the ruptured zone. Internal insulation was gone in this zone and there was insulation loss in other zones. Conditions relative to adequacy of water supply at time of failure are not known.

Case 2: The inlet line suffered a major rupture. No significant loss of internal insulation was found. Conditions at time of failure are not known.

Case 3: A bulge and rupture occurred at the top of the inlet line near a thermowell connection. There were three other bulges evident near three similar thermowell connections. Local insulation voids were found at each of these locations and at one of two similar locations where no bulging had occurred. There was no significant insulation loss elsewhere. Violent boiling had been noticed several hours before and water supply rate had been increased. The jacket had run dry earlier.

Inspection during downtime for repairs disclosed a shroud section collapse in the transfer line from the secondary reformer to the waste heat boiler and a bulge and crack in the pressure shell at the top in this zone. Insulation was missing in this zone.

Case 4: When a leak and flame were observed at a thermowell nozzle on the transfer line from the secondary reformer to the waste heat boiler, the unit was shutdown. Internal inspection showed an internal shroud section was bulged and split, and insulation missing. About a year before, extensive insulation was missing at the same location but the shroud required only slight repair and no shell failure occurred. In each instance, inspection disclosed that there was considerable insulation loss in the waste heat boiler sections.

It is pertinent to note that two plants, upon observing increased boiling on secondary reformer inlet transfer line or exchanger jackets, checked insulation and finding considerable insulation loss, corrected the condition before failure.

Water jacket advantages 1 and 2 have more than proved their value in secondary reformer service. In addition to the reformer service cited here, ICI reported only one failure and that was due to lack of jacket water.

Heat exchangers and transfer lines

Service experience on heat exchangers and transfers lines with shrouded lightweight insulation on large train ammonia units has not equaled that on the secondary reformers. In the case of the exchangers, four shell failures are cited. In three of the instances, severe abnormal heating was probably due to shroud malfunction permitting gas by-passing, and, in the other case, to appreciable insulation loss and, possibly, to shroud malfunction. Actual shell failure under these conditions was attributed to loss of water in two cases. In the other cases loss of water level before failure cannot be definitely established but the character of all failures is similar. In several other instances of similar heat input conditions the jackets performed their safety function and no shell failure occurred.

With respect to the transfer line failures, water level conditions immediately prior to failure are not adequately known for the three inlet line cases, but the failures are difficult to explain unless the supply of cooling water was inadequate. In Case 3, a very high heat input condition was evident by the violent boiling and the need for increased water supply for level control. Bulging and initiation of failure may have occurred during the period when the jacket was dry. Outlet line failure Case 4, and the bulge cited in Case 3, are not satisfactorily explained in the absence of inadequate water level at the time of failure or at some earlier time.

Exchanger and transfer line jackets have been subjected to abnormal heat inputs due to shroud malfunction, insulation voids or loss. Wrinkling and buckling of the shrouds has occurred. The operating conditions, temperature cycles, condensation of steam at startup and shutdown, and vaporization on rapid heating undoubtedly impose severe demands on the shrouds and insulation. Where water injection has been used for boiler tube scale removal, shroud damage and cracking potential is materially increased. Some shroud difficulties and voids have resulted from inadequate fabrication quality or insulation placement controls. These have generally been identified on the first internal inspection and corrected.

Service performance reflects the integration of all elements; internal insulation, including its design, materials and quality controls, water jacket provisions and instrumentation, maintenance, and operation. Insulation currently being used in exchangers and transfer lines is a low silica bubbled alumina castable similar, except for lower density, to that now used in the secondary reformer vessels. The change to low silica type was initiated on new construction in 1967 to combat the problem of tube fouling by silica transfer deposits by reducing the sources of silica. Dial (*5*) cites its properties and suitability. Alternate constructions involving the use of unshrouded two layer refractory lining such as that described by Dial, or a single layer dense refractory castable, offer the promise of eliminating shroud maintenance and allowing easier inspection of the insulation, although they have possible disadvantages of their own (*4*). M. W. Kellogg has studied the feasibility of such construction retaining water jacket protection, and is prepared to offers it on new designs for transfer lines. Possible application to waste heat boilers is under development.

Recent experience indicates that there is a great need for increased operational awareness so that deteriorating lining may be quickly dealt with. Observation and recording of net feed water rates at various ambient and operating conditions as a measure of steam make would seem to offer the most practical approach, with instrumentation selected to facilitate this task. Operation without proper water level and water quality must be avoided and significant changes from normal performance carefully investigated and conservative judgment exercised relative to unit shutdown. In two instances of heat exchanger shell failure, the low level alarm was not operating. In one case, the operating company reported they have added several metal temperature measurement points on the shell below the normal liquid level to supplement the low level instrumentation.

Some might ask whether water jackets are necessary at all or if linings might be designed for bare shell operation permitting metal temperature monitoring by such means as heat sensitive paint and temperature sensing instrumentation. These are the same questions which faced M. W. Kellogg's engineers in 1955. At that time some units without jackets were in successful operation. Five of these were exchanger units with the same lightweight internal insulation and operating conditions similar to those in Table 1, but much smaller. It was not necessary to add jackets to them. Since that time one secondary reformer, at lower pressure than current units, went into service at client decision without jackets and has performed satisfactorily. A Kellogg sponge iron plant has considerable piping operating at 1,650°F with a two layer refractory lining consisting of brick and poured insulating concrete. We are also aware that there are other vessels and piping operating in high temperature service without jackets so we cannot assume that water jackets are essential for all applications.

When using refractory insulations, design calculations can be made to investigate the stress conditions in the lining and shell and determine whether or not a radial gap may exist at the shell (*2*, *3*). However, Huggett (*2*) points out that concrete is variable in its properties, particularly shrinkage, and that practical considerations of this and other factors make it virtually impossible to rely on such calculations. Thus, from a design standpoint the designer is handicapped relative to assuredly predicting acceptable performance when not using jackets. For some design conditions, particularly where a high pressure drop and/or high fluid heat transfer coefficient is involved, the assured maintenance of a state of compression in the lining attainable with the temperature control afforded by water jackets may be necessary for operational performance as well as safety.

Water jackets clearly provide heat removal capacity for abnormal conditions well in excess of that of a bare shell and can materially add to the safety performance of internally insulated equipment. That there are disadvantages to both bare shell and jacketed design is recognized so that a choice cannot be entirely clear cut. As previously noted, it was the opinion of M. W. Kellogg's engineers that overall safety would be significantly enhanced by water jackets and, further, that advantage 2 would improve initial and continued thermal performance. Time and experience have proved this to be true.

Acknowledgment

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Literature cited

1. Rossheim, D. B., J. J. Murphy, G. P. Eschenbrenner, and R. S. Eagle, "Pressure Vessel Overtemperature Hazards," ASME Paper No. 59-A-319 (November, 1959).
2. Hugget, L., "Materials Technology in Steam Reforming Processes," C. Edebann, ed., p. 305, Pergamon Press, London, (1966).
3. Wygant, J. F., and M. S. Crowley, "Design of Monolithic Refractory Vessel Linings," American Ceramic Society Bulletin, **43**, No. 3, 173 (1964).
4. Kratsios, G. and W. P. Long, "Safety in Air and Ammonia Plants," **10**, 8, AIChE tech. manual (1968).
5. Dial, R. E., "Safety in Air and Ammonia Plants," **10**, 29, AIChE tech. manual (1968).
6. Venable, Jr., C. R. "Refractory Requirements for Ammonia Plants," paper presented at American Ceramic Society Meeting, Chicago (April, 1968).
7. James, G. R., "Safety in Air and Ammonia Plants," **10**, 1 AIChE tech. manual (1968).
8. Jacobowitz, J. L., and L. A. Zeis, "Safety in Air and Ammonia Plants," 10, **11**, AIChE tech. manual (1969).
9. Kreith, "Principles of Heat Transfer," 2 ed., pp. 434-480, International Text Book Co., Scranton, Pa.
10. McAdams, "Heat Transmission," 3 ed., pp. 398-399, McGraw-Hill, New York.
11. Mayo, H. C. "Safety in Air and Ammonia Plants," **10**, 109, AIChE tech. manual (1968).

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