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30 Years Of MSR Restoration And Upgrade, An Experience Base For Future Designs

Abraham L. Yarden
Thermal Engineering International
California, USA

Clement W. Tam
Thermal Engineering International
California, USA

Akira Okabe
Hitachi, Ltd., Power & Industrial System, Japan

Abstract

Many existing Nuclear power plants world-wide are undergoing a new birth – approaching the end of their initial licensing period, their generating capacity is now being uprated through a recognition of the conservatism of their initial design; their MSRs upgraded to restore deteriorated performance, eliminate historically high maintenance costs and to meet the added needs of this plant uprating; and re-licensed for continued operation into the years ahead. An important aspect of this process is the recognition that the moisture separator reheaters (MSRs) can no longer be considered to be mere balance-of-plant (BOP) auxiliaries – their significant impact on MWe generation, plant operating stability, and reliability has become increasingly appreciated. Over the years in excess 90 sets of MSRs have been already redesigned and reconstructed worldwide.

Over the past 30 years, MSRs of every type, and lately MS vessels have been upgraded for a variety of operational reasons to take full advantage of the advancing technology that has emerged on many fronts. While this has permitted the plant upratings currently in progress and decreased the unacceptably high maintenance costs and MWe loss experienced, it has also, perhaps more importantly, pointed the way toward the efficient, reliable MSR designs required for the new generation of much larger nuclear power plants being built and planned for the years ahead.

1 INTRODUCTION

There are a wide variety of specific moisture separator reheater (MSR) designs and several moisture separator (MS) designs for original equipment, which were created over the years. For this reason, MSR and MS redesign and reconstruction projects have, of necessity, been unique to the specific design – there is no standard to the MSR or MS upgrade process. These projects run the gamut from mere moisture-separation system replacement all the way to total redesign and replacement of entire MSRs including the vessels. To illustrate both the range and specifics of these successfully completed projects, several are cited here. Overall, this will clearly show that the nuclear industry has in hand the wherewithal to meet the continuing needs of today and challenges of the future in providing the advanced MSR technology that will assure long-term successful operation of the new, large LWR nuclear power plants to come.

A good example of this is the relatively recent advent of nuclear power in the Peoples Republic of China which has given stimulus to new MSR original-equipment designs. Although its first indigenous nuclear power plant, a 300-MWe PWR at the Qinshan site, was equipped with MSRs largely similar to the licensor's original design, the four new 700-MWe units now under construction and nearing completion employ advanced MSR designs and are expected to show improvements in performance, reliability, and life over those recently built in east Asia using standard earlier designs. These new designs at Qinshan do not depart from the well-established design principles of the past. Rather, they evolve from them and improve them in areas of real impact – size, accessibility, flow streamlining, and resistance to flow-assisted corrosion (FAC).

Broadly speaking, MSR components can be classified as moisture separators, reheaters, and vessels. Within each of these component classifications, there exist a wide variety of active and passive element considerations – thermal, hydraulic, mechanical, metallurgical, radiological, architectural, and structural for example -- including unique installation problems and schedules.

2 MOISTURE SEPARATORS (MS)

The efficiency of originally installed moisture separators (MS) in non-reheat and reheat nuclear steam cycles, has always been doubtful. Efficiency levels achieved in old MS technologies lacked means of quantification, and assumptions made regarding their efficiency were highly optimistic. As a result these MSs in reheat cycles have traditionally been unnecessarily high consumers of inlet throttle and/or extraction steam, if only to evaporate moisture not mechanically separated. This inefficiency was frequently exacerbated by poor HP-turbine exhaust distribution across the MS elements.

Today's advanced MS design technology includes two basic parts that address both the former shortcomings – perforated plates immediately upstream of the mechanical moisture separator chevron vanes now can assure nearly equal HP-turbine exhaust distribution across the entire open face of the MS chevron vanes, and modern double-pocket chevron vanes that result in essentially 100-percent MS efficiency. Figure 1 show the "V" arrangement of the MS elements in a modern MSR configuration. Figure 2 is a photo of the installation of the flow-redistributing perforated plates, just upstream of the double-pocket chevron vanes. Figures 3a and 3b show a MS double-pocket chevron vane arrangement and a photo of a small section of it.

While moisture separation section reconstruction, using the modern-technology components has singularly contributed to increases in MWe output of past MSR and MS vessel redesign and reconstruction projects, the MS contribution is usually combined with other factors, such as reheater restoration which also constitutes a major contributor. However the specific MS contribution toward these ends can be established in the case of recent projects at two non-reheat nuclear power plants in the central US that use moisture separators only, and in a recent MS section upgrade project at a Carolina Plant MSR.

In the first case, there were four, essentially duplicate 820 MWe BWRs at the Dresden and Quad Cities plants, built approximately 30 years ago. Each incorporated four original equipment manufacturer (OEM) moisture separator vessels (MSs), reflecting the design technology of their time. These MSs are essentially 24-ft (7.3-m) high 13-ft (4-m) wide vessels containing four vertical moisture-separator panels which are slightly offset vertically, Fig. 4. At full load, 306 kg/sec (2,432,000 lb/hr) of HP turbine outlet steam at 15.5 BarG (225 psig) and approximately 88-percent quality enters each of these MSs and is guided to the two upper and two lower panels by a V-shaped deflector, followed by a full-faced baffling plate with two upper and lower openings, whose distribution effectiveness was questionable as was their ability to reduce the high turbulence of the incoming steam. There is conclusive evidence that the dry steam originally anticipated for delivery to the LP turbine was never really achieved.

While several redesign and reconstruction options existed, optimization pointed to the replacement of the original single-pocket chevron vanes with modern-technology double-pocket vanes. One particularly unique obstacle to be overcome in order to fully utilize the repaired, existing internal panels was the support structure. The standard, single-pocket, moisture-separation chevron vane panels produced 20 or 30 years ago measured 250-mm (10-in.) deep by 2.2-m (91-in.) long. Today's, advanced-technology, double-pocket chevron vane panels are punch produced to a standard size of 200 mm (8 in.). An earlier solution here involved installing structural spacers in both dimensions to accommodate the standard new chevron vane panels into the existing support structure.

At Dresden and Quad Cities, all of these MS structural modifications and chevron vane panel installations had to be accomplished through a 600-mm (24-in.) diameter manway into each MS vessel, and installation time was limited to 16 days. Therefore the installation of perforated plates was excluded. The initial design target calculated was to achieve a 7-MWe gain in each unit. After MS reconstruction, excluding perforated plates, and discounting other outage improvements, the actual gain in each of two plants was 11 MWe. The third gained 6.5 MWe. The fourth will be retrofitted soon.

Lessons learned from these installations lead to significant further enhancement of the new design. This also applies to a later version of these old OEM MS vessels with a conical distributor instead of a V-shaped deflector and a baffling plate. These enhancements involved a deeper chevron vane core blade which extends to 250 mm (10 in.), so as to fit into the existing support frame with no need for compensating strips. Restructuring the four-panel, two-tier arrangement into an eight-panel, four-tier arrangement provides for two additional intermediate drain channels and shorter chevron vanes, i.e. 1 m (42 in.). This four-tier arrangement prevents accumulating moisture buildup at the chevron footing and provides ample gravity drainage inside the vessel which is fully vented. Fig. 5.

3 MSR REHEATERS

MSR reheaters have traditionally been fabricated in a wide variety of thermal and physical designs by the various turbine-generator OEMs over the past 30 years. In each case, these design configurations have been intimately related to the MSR shells and internal structures employed. For example: single-stage (taking heating steam at turbine throttle temperature and pressure), two-stage (taking both steam at throttle temperature and temperature and extraction steam from a mid-point in the HP turbine), a single tube pass (involving straight tube heat exchanger) 2-tube pass (involving a single U-tube heat exchanger), and both an old- and new-design 4-tube pass (involving a U-tube heat exchanger partitioned at its header to create 4-passes configurations) are all commonly encountered. Others, such as two U-tube banks connected in series through a common header and a 6-tube pass configuration have also been in limited use as original or replacement equipment.

In addition to usually having to take into account the physical constraints imposed by the MSR shells themselves, it has occasionally been necessary economically to design around existing internal structural requirements. In all cases, however, the overall goals of MSR reheater redesign and reconstruction remain constant – take full advantage of today's advanced technology in terms of physical design and metallurgy, eliminate wasted steam through minimizing excess purging steam used for tube venting and ineffectual bypass steam control, minimize cycle-steam pressure drop, increase MSR outlet superheat as much as possible (minimize the terminal temperature difference (TTD)). The goal here of course, is to restore MWe lost through the years as a result of inadequate initial design and/or operational deterioration overtime, and further enhance MWe output to help meet the established uprated repowering goals and assure continuing operational stability and reliability in the years ahead.

Regardless of the several constraints frequently restricting the complete redesign and reconstruction of MSR reheaters, several steps can almost always be taken to improve performance and reliability. These include such things as optimizing heat transfer by retubing with Type 439 stainless steel finned tubes having more (27 per inch) fins. Sometimes this step also involves using different diameter tubes and rearranging their geometry, Comanche Peak, Units 1 and 2, is an example. Many reheater tube damages and failures, over the years, have resulted from variable thermal stresses and physical distortion in their rigid support structures, due to high temperature differentials. This old design has now been replaced in many installations by a so-called flexible (slip-plate) support structures, Fig 5, that eliminate these problems. In addition, bypass steam losses at the outside tube columns can be drastically reduced through the use of flow restricting bars welded to the slip-plates themselves, Fig 6.

Some years ago, it became obvious that a revised 4-pass reheater design inherently possessed a distinct operating advantage over many of the older installed 4-pass reheater design then installed. Fig. 6 summarizes this essential arrangement difference. In the old 1-4-3-2 pass design, considerably more steam was required to "drag" the accumulating condensate *up* between the 3rd and 4th passes. In the modern 1-3-4-2 pass design, this condensate flow between the 3rd and 4th passes is *down*, driven by gravity and is con-current with its steam phase. Thus the presence of excess steam, at this 3rd to 4th pass point, to drive the condensate uphill is not required. In addition, modern MSR reconstruction practice call for the installation of a manual control valve at the 4th pass discharge line instead of a commonly used fixed orifice to control the exiting condensate steam flow. This valve can then be adjusted periodically to minimize any excess steam flow. Its adjustment is benchmarked to temperature sensors installed in the tube outlet ends, which provide actual readings.

One example among many of this modern 4-pass redesign and reconstruction feature was carried out some years ago at Duquesne Light's 888-MWe PWR Beaver Valley nuclear power plant. As a result The TTD was reduced from 31C° (56F°) down to 11C° (20F°). While the expected output gain was 12 MWe, they actually gained 15.6 MWe (including moisture separator efficiency improvement and reduction in pressure loss).

Where space permits, older 2-pass reheaters can be replaced to advantage by advanced design, 4-pass reheaters. This was done at the Indiana Michigan Power Company's 1089-MWe PWR Donald C. Cook Nuclear Power Plant, Unit 1. Here the TTD was reduced from about 11C° (19.8F°) to 5C° (9F°) and the actual test power output gain was 7 MWe. Figures 7a and 7b show the old 2-pass arrangement and the new 4-pass design. Figure 7b also shows the steam/condensate paths which minimize excess steam consumption, while increase its relative purging capability (excess steam ratio).

4 MSR VESSELS

Over time, MSR vessels can suffer severe internal erosion in areas of extremely high steam velocity or high turbulence. In general this damage can be repair welded, but it can be expensive and only temporary. A unique situation arose in the redesign and reconstruction of two, 954-MWe PWRs at Virginia Power Company's North Anna Nuclear Generating Station. In that case, the costs and outage time required to weld-repair the shells was deemed to be excessive. It was therefore decided to entirely replace the MSRs with completely factory-built replacements. This, of course, allowed the redesign and reconstruction process to take essentially full advantage of advanced MSR technology. Thus, the potential for future corrosion/erosion damage was eliminated through new design and improved metallurgy. This involved restructuring the internal flow paths for reduced impingement, eddies, and turbulence to minimize erosion/corrosion (EC) as well as utilizing proper materials to endure EC. In addition, cost-effectiveness of this complete MSR replacement process further benefited from the enhanced use of station personnel throughout the installation process, the ability to use conventional rigging to bring the complete MSR to the turbine deck, and the main turbine crane to set it in.

A comparison of Figs. 8a and 8b clearly shows how this design freedom was fully utilized in Unit #1 to produce the latest advanced technology in North Anna's new MSRs. Figure 9 is a photo of one of these completely factory built MSRs being installed at North Anna. The shell-side pressure drop was decreased from approximately 158 kPa (22 psi) to negligible 55 kPa (8 psi); the TTD dropped from 23C° (41F°) to a nearly unmeasurable 3C° (5F°); and an average actual power output gain of 14 MWe was achieved.

5 MSR INSTALLATION

Field installation of redesigned and reconstructed MSR components – moisture separation elements and reheaters of various configurations – always presents many challenges. Figure 10 is a photo of the reheater installation at KEPCO's Kori 2 unit in Korea. Frequently cramped conditions are encountered in the MSR component installation process. In the first place, time is always a critical element; usually this field work must stay within, or at least minimally exceed, otherwise short scheduled outage time. This requires an exceptionally high degree of pre-planning and leans heavily upon the lessons learned in prior MSR restoration projects. The game plan always includes contingencies.

Figure 11 shows the solution to a recent unique problem at Southern Nuclear's two 820- MWe BWR at Plant Hatch in the southern US where clear space did not exist to withdraw and lift out, and then re-insert the reheater bundles. Not only did a wall have to be removed, but also the bundle assemblies had to be lowered at an angle, leveled, and only then inserted into the existing shells.

Figures 12a and 12b show another installation problem at the 975-MWe BWR Cofrentes nuclear power plant in Spain. Here the tube bundles to be removed were not self-supporting. Hence they had to be removed onto a supporting "tray" at the two levels required for the two reheater bundles, one above the other, involved per MSR shell.

A very recent innovation in the design and reconstruction of MS sections was successfully carried out at the Duane Arnold Energy Center's 656-MWe BWR in the central US. Since this is a BWR, personnel radiation exposure was an important consideration in any maintenance operation or component reconstruction operation. To minimize personnel radiation exposure during the MSR redesign and reconstruction, structures containing the chevron moisture separator banks and integral perforated plates were prefabricated in the factory and shipped as individual modules to the plant site, Fig 13. In addition to greatly speeding up the installation process and minimizing personnel radiation exposure, the added benefits of in-shop quality control vs. field assembly within the MSR shell are obvious.

6 ADVANCED MSRs FOR TOMORROW'S LARGER NUCLEAR POWER PLANTS

The wide variety and extent of experience gained over the past 30 years in the redesign, reconstruction, upgrading, and restoration of over 90 MSR sets of essentially every design (with the continual application of the lessons learned) have enabled the nuclear industry world-wide to meet and overcome the inadequacies in MSRs originally considered to be mere BOP accessories. With this wealth of experience to lean on, and the current appreciation of their potentially high impact – for good or bad – in PWR and BWR nuclear power plant cycles, future MSRs will play an increasing, direct role in plant design.

As nuclear power unit sizes increase by as much as 50 percent and more, i.e. from the 1000-MWe range up to perhaps the 1750-MWe range as now being contemplated in Japan, this 30-year experience becomes invaluable. For example, certainly current MSR physical size cannot be merely prorated to match unit size increases, nor can a more complex design with multiple shells be physically or economically considered as a viable answer. So what factors do produce workable solution?

One is volumetric efficiency increase – the elimination of wasteful internal structures and the functional use of idle, or residual, space – that must be achieved. A recent example of this concept was the MSR replacements at the North Anna Nuclear Generating Station in Virginia, USA during its uprating from 900 MWe to 954 MWe. Figure 8a, when compared to Fig. 8b, clearly shows how idle space was utilized. A wider, octagonal, 4-pass reheater, using a modern configuration replaced the original rectangular reheater and produced increased performance. Advanced, double-pocket chevron vanes preceded by perforated plates for better wet-steam distribution increased moisture separation efficiency. One must remember, however, that many constraints remained at North Anna – vessel diameter and length, for example.

This example points up the benefits of the current rethinking of the place of the MSRs in conceptualizing the larger nuclear power plants of tomorrow. No longer are they a mere turbine auxiliaries; they are now a specifically identified, major component. Therefore, MSR needs now play a major role in large-plant turbine-deck design. This, of course, leads to full MSR performance optimization based on the wealth of experience gained over the past 30 years.

New, larger nuclear power-plant licensing and predicted plant lives in the 60-year range (essentially doubling the past's original licensing practices) require very special attention to those factors that have limited MSR life in the past. Flow-assisted corrosion (FAC), sometimes called "wall thinning" or "erosion/corrosion," can no longer be tolerated if this extended plant is to be achieved. This means that the steam-flow streamlining lessons learned over the years with regard to such design refinements, such as controlling wall-rubbing and gouging steam velocities, areas of frontal steam-flow impingement, and the critical relationships between cycle chemistry (steam/water) and endurance chemistry (carbon, low-alloy, and stainless steels) must be carefully considered in future MSR designs.

Another promising development for possible future use is the high-velocity moisture separators (HVMSs), Fig. 14. As a "gross" moisture-separation system (increasing steam quality from about 85 percent to as much as 97 percent) in the HP turbine exhaust piping ahead of the in-vessel chevron-vane, this greatly lightens the hydraulic load on the in-vessel MS section. In one case, the swirling steam flow in the HVMS centrifugally "throws" the bulk of the moisture to the piping wall where it is peripherally collected as condensate and, through a loop seal, removed by gravity to a low-pressure receiver. In other cases, a steam feed is needed to induce purging of the condensate into a valve, controlling its flow to a lower-pressure sump. This possibility of an HVMS-in-series with the in-vessel MS section can have several advantages: (1) It assures essentially total system moisture removal, and (2) The pressure drop created by the HVMS can be more than made up by reduced losses of the dryer downstream steam flow. Some unsubstantiated reports claim that this technology also produces a reduction in piping erosion.

While innovation is an evolving process, care must be taken to avoid unproven design "fads" and confine this process to "milking" improvements for all their worth out of proven systems.

As a result of the lessons learned in the past 30 years of MSR redesign, reconstruction, restoration, and upgrading experience MSRs stand today at their pinnacle of design and performance as major plant components. Therefore the nuclear power industry can be confident that the MSR component in the much larger units in the future will perform optimally throughout their extended plant lives.

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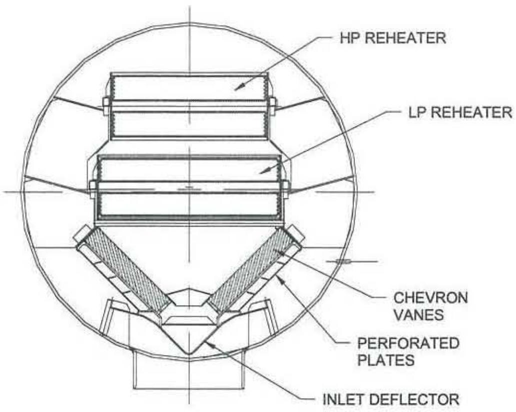
ILLUSTRATIONS



A MODERN MSR ARRANGEMENT
Figure 1

MOISTURE SEPARATION SECTION - INSTALLATION
Figure 2

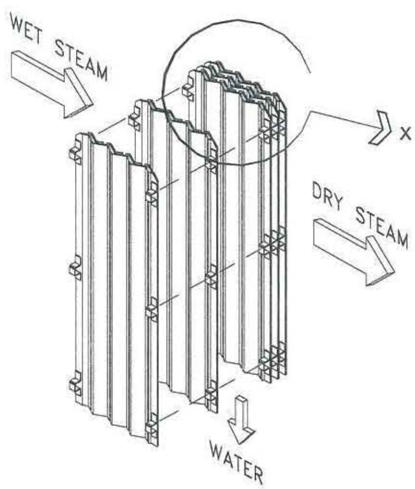
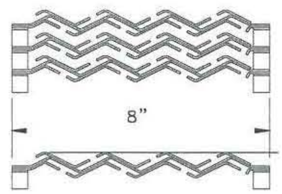


Figure 3a



Detail X

DOUBLE POCKET CHEVRON VANES

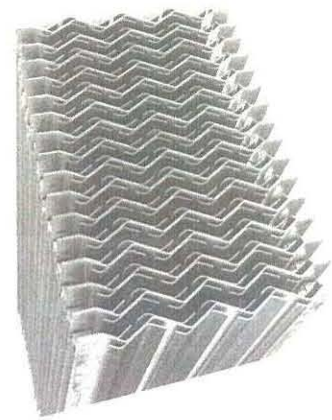
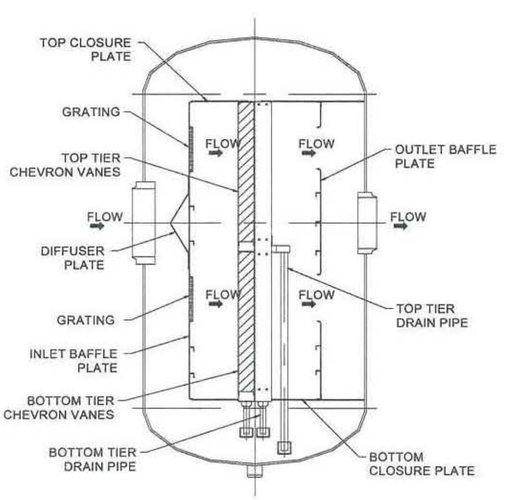
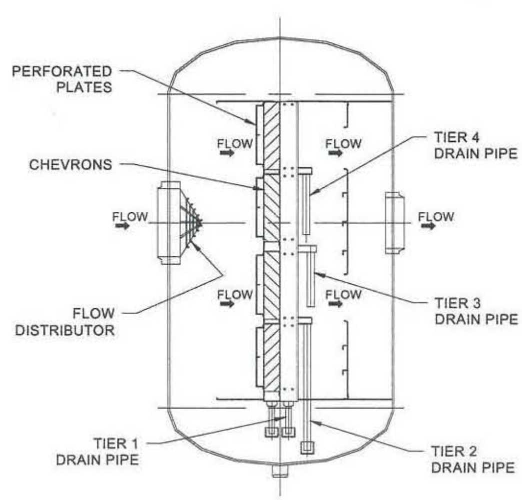


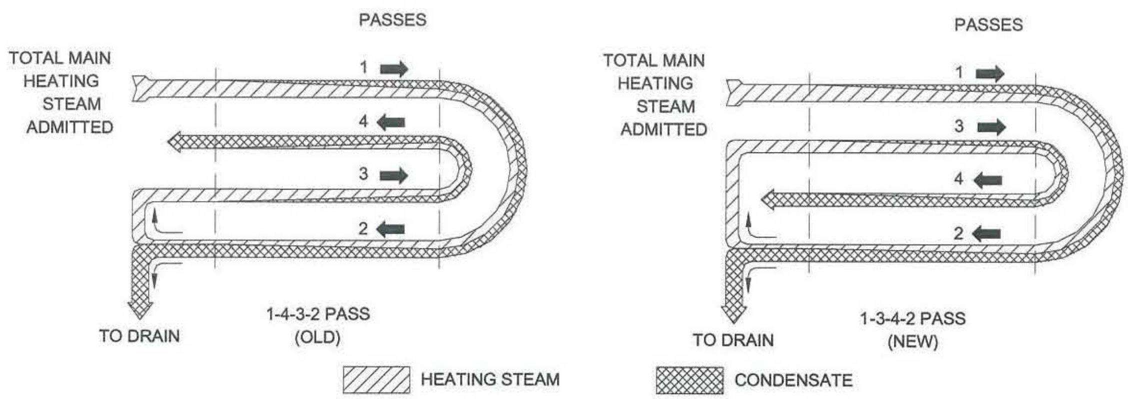
Figure 3b



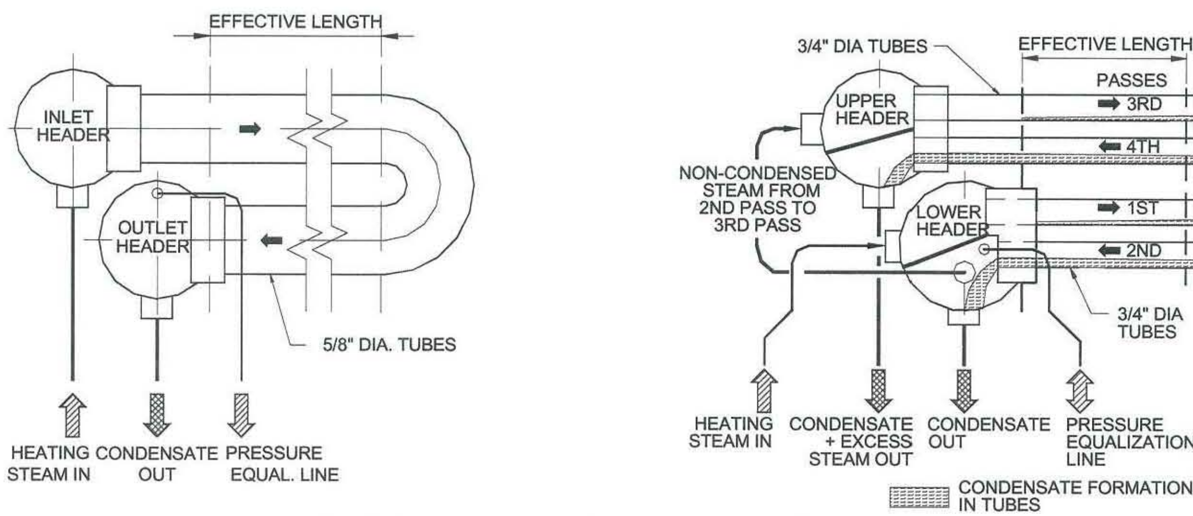
ORIGINAL ARRAGEMENT OF MOISTURE SEPARATOR
Figure 4



RECONSTRUCTED ARRAGEMENT OF MOISTURE SEPARATOR
Figure 5

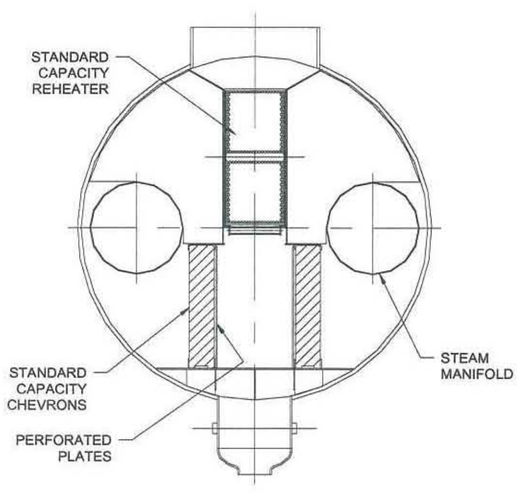


4-PASS TUBESIDE ARRANGEMENTS
Figure 6

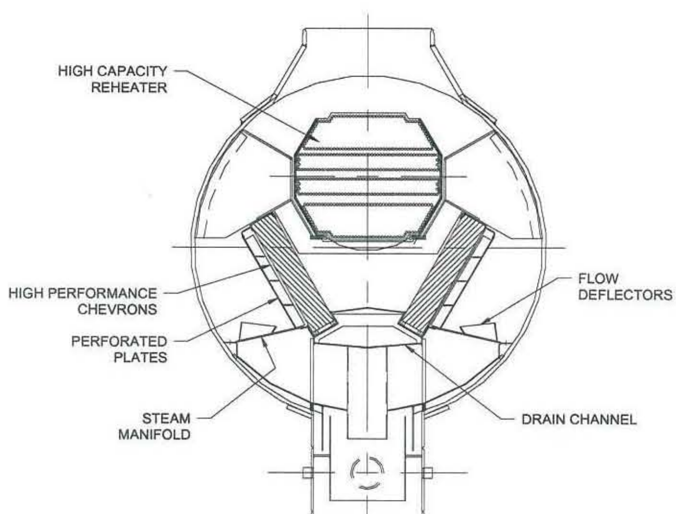


AN ORIGINAL (a) AND AN ADVANCED (b) 4-PASS DESIGNS

Figure 7a **Figure 7b**



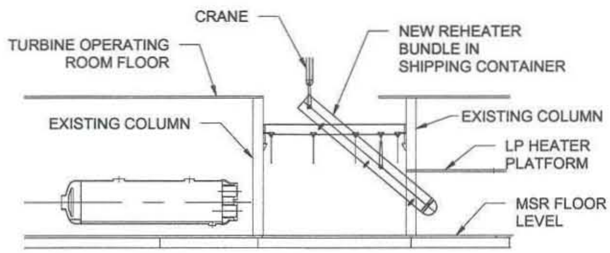
ORIGINAL MOISTURE SEPARATOR REHEATER
Figure 8a



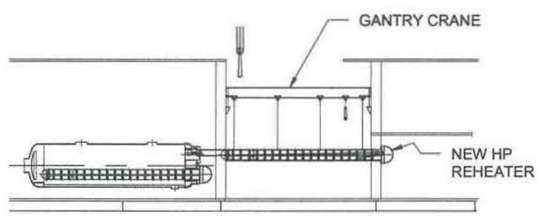
NEW MOISTURE SEPARATOR REHEATER
Figure 8b

A NEW MSR VESSEL - INSTALLATION
Figure 9

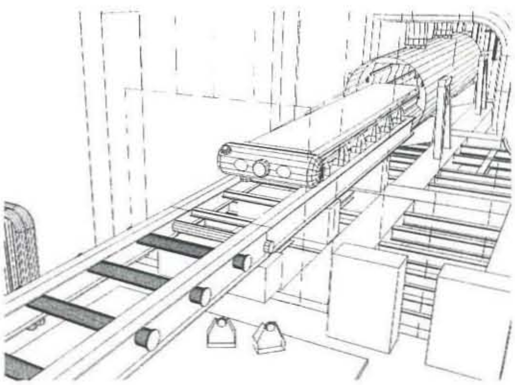
REPLACEMENT REHEATER - INSTALLATION
Figure 10



SETUP FOR HOISTING DOWN A NEW LP REHEATER (ENCASED)
Figure 11a



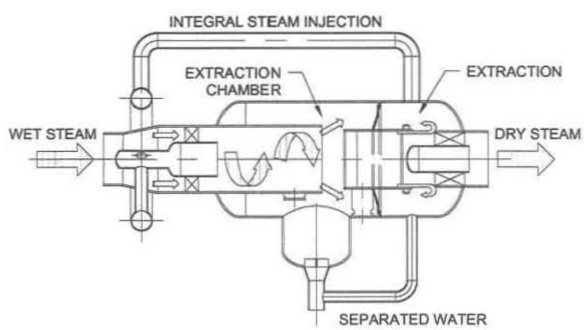
SETUP FOR INSTALLATION OF NEW HP BUNDLE
Figure 11b



REHEATER INSTALLATION - STUDY
Figure 12a

REHEATER INSTALLATION - ACTUAL
Figure 12b

MOISTURE SEPARATION MODULE INSERTION
Figure 13



HIGH VELOCITY MOISTURE SEPARATOR (HVMS)
Figure 14