REAPPLICATION OF TURBOMACHINERY

by

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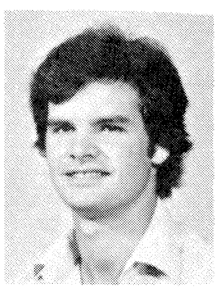

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ABSTRACT

The reapplication of equipment can be attractive and rewarding when the proper situation warrants. The main factors that encourage consideration of this path can include simple economics, convenience, or possibly a more expeditious route for a project. This also offers lower risk when the equipment is known and proven. Reapplying equipment can produce significant savings of capital project funds which equates to immediate gains, as well as the reward of accelerated returns due to a shorter schedule. However, the probability of finding a perfect match for a new application is remote, and hence, a redesign is normally required.

Various options the end-user can consider in performing redesign work are reviewed, along with the logic that supports the various options, the requirements and paths to be considered. Example case studies will be examined.

INTRODUCTION

The reapplication of turbomachinery may be considered for a variety of reasons. They may be due to the fact that the changes are so minor to an available piece of equipment that it would be foolish to overlook the opportunity. Another may be because the possession of such equipment by the user offers many benefits including familiarity, similar machine in service, maintenance, and spares history, etc. The user can normally gage the applicability of a machine for an existing or future facility whereby the rework of the equipment would be relatively simple and affordable.

Whether the equipment is in the possession of the owner or the equipment is purchased outside in the available market place, it is often concluded that the main reason to reuse equipment is the savings *vs* the cost of new equipment. Although the ratio of used equipment cost *vs* new equipment cost can be as low as 15 percent, the user must note that after accounting for increased engineering requirements and the related installation costs, the savings to a project on a capital expenditure basis is reduced. Typically, if the reused equipment requires serious redesign, the project savings is normally in the 30 percent range. Timing is the most significant reason to consider the reapplication of proven turbomachinery. When the reapplication requires extensive design changes and serious physical changes to the equipment, it will be found that shortening the overall project schedule is still attainable.

Projects up for consideration have a definite return and the sooner this return can be realized, the more attractive the opportunity. It can be shown by review of any project schedule that the major duration in the overall plan is always specifying purchasing and delivery of the major equipment (Figure 1). If this one year duration (typically) can be reduced by as much as six months, the value of the project per day is enhanced by that amount of money. Occasionally, there are projects that are close to the break point, and by reducing the cost of the major equipment, the project will be a "go" *vs* a "no go" situation. In overall dollars, however, it will always be the project schedule that will generate the significant savings, and will become the driving force for the consideration of this action.

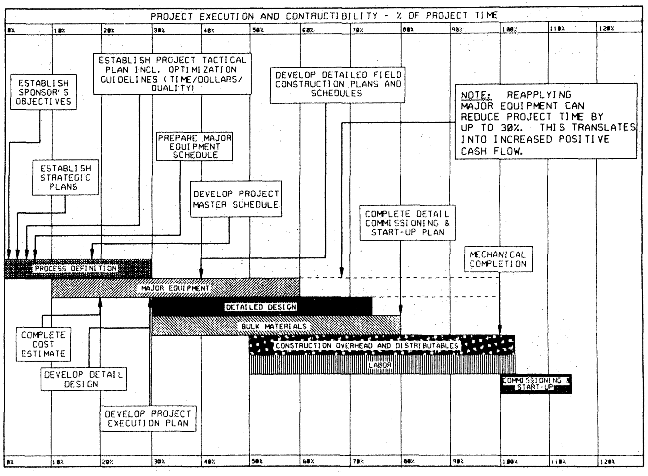

Figure 1. Typical Project Timing Outline.

DISCUSSIONS

Expansions of facilities to meet demand offer the opportunity for reapplications where the present equipment is limited in its production capabilities. Several different paths can be considered toward effecting the outcome of the modification, for example:

- At shutdown the existing equipment can be modified in place (should be considered for minor revision).
- Locate another machine which is designed for the new service and skid build or modularize the new package so it fits the existing "footprint" with minor foundation revisions.
- Skid or stick build another machine effectively in parallel with the existing machine. Limit shutdown activity to minimum tie-ins, etc.

The project schedule is critical in considering the work on equipment *vs* the serious downtime situation which would be created. This gives prudence to considering the latter path of locating equipment that can be modified to match the project requirements, which is then engineered, fabricated, and delivered to the site. Construction can be completed so that one turnaround is required without any serious reduction in production capabilities due to a long outage. Other possibilities may simply be the relocation of complete process units or equipment from one site to another. This would also normally require various changes to the process, whereby consideration must be given for either aerodynamic/hydraulic or mechanical revisions to the equipment, so that it fits in the new location and matches its requirements to gain the overall benefits of either production capability or performance. The new facility will offer the most logical opportunity to consider the reapplication of equipment.

When turbomachinery comprises the majority of the equipment required for the project, it is probably a good candidate for utilizing this method to shorten a capital project schedule. If other long duration major equipment is also required, the opportunity is diminished, but not completely discounted. For critical, single-train systems, an early installation of equipment can allow additional time for checkout, commissioning, etc.

APPLICATIONS OF RETROFIT MACHINES

Process changes, whether it be technology improvement, unit expansion, etc., account for the majority of applications where reapplied equipment is used. In the examples presented, two turbocompressor applications are discussed. For such compressor modifications, the normal items that must be considered are:

- flow capability of the equipment (surge, stonewall).
- molecular weight changes.
- suction conditions (pressure, temperature).
- compression ratio.

Once agreement is obtained as to the best requirements for the new application, agreement should be obtained for the system resistance intersection of a head/flow curve. Once the application engineer has a clear target on an estimated head/flow curve, he can then seriously begin to review the options for possible machinery that will match these new requirements. One should be warned to never try to make the process match the equipment. Process equipment normally runs 8,000 hr/year. The process should always be optimized, and the equipment must match the process requirements to attain maximum financial gain. When the process requirements are known, the criteria for equipment is also clearly defined.

The search for equipment inhouse and out in the market place should proceed with a clear conception of what type of equipment would be sought if one were buying it new. The search for inhouse equipment should focus on proven machines which can be modified to meet the new conditions. Areas which can be investigated towards achieving the new design include:

- speed changes (via driver, gearbox, etc.).
- impeller modifications (diameter changes, complete redesigns).
- materials of construction.
- driver type.
- complete rotor change.

If it is required to go to the outside market, caution must be exercised in the review of equipment in its initial inspection prior to purchasing along with agreeing to the value of the equipment after a thorough inspection. Inspection includes, as a minimum, a visual survey of the machine and related auxiliaries. The time gained in acquiring a turbine for a reapplication can be totally wasted if it is determined at a later date that the trip throttle valve was not in the original pile and a new one is required, for example. Internal inspection is often limited to main connections and minimum inspection covers. A user should not be hesitant in requesting some reasonable disassembly for further insight. Another means, for instance, may utilize the advantages of borescopes to view critical rotor areas and perhaps avoid enormous expense at a later date. Inspection also means researching and acquiring drawings, data, and related available materials.

Purchasing used equipment can be very risky. Once a piece of equipment is located and identified as a suitable candidate for an application, the value can be agreed upon through negotiation. It is recommended that the purchase order contain a waiver as to the value differential due to problems located at disassembly and/or after a thorough inspection including all nondestructive testing (NDT) is complete and satisfactory. Inhouse equipment must also be reviewed thoroughly, although its pedigree is normally understood, and can be trusted due to the availability of inhouse records.

At this point, the advantage of the project must be demonstrated to proceed with the reapplication of available equipment as opposed to purchasing new equipment. It is the responsibility of the applications engineer to demonstrate in a normal bid tab fashion the clear economic advantage of reutilizing existing available equipment. The amount of engineering in a serious modification to equipment is actually very high and of long duration. When serious rework is required, a thorough review by experienced people is required to assure that all the possible problems, contingencies, and costs are included in the price of the used machine *vs* new. One must be prepared to be challenged and to demonstrate the clear economic advantage of utilizing old equipment. The benefits are often questioned by operations, maintenance, and even project management. In doing an economic evaluation, the project schedule will always be the overpowering factor which will push for the utilization of existing equipment.

Once it has been decided to proceed with the reapplied machine, which tasks will be performed inhouse must be considered, as opposed to purchasing the services on the outside. Even when the user has the ability to perform all the required engineering inhouse, consideration must be given to farming all or portions of the work out with subsequent review of the other's work. Whether the OEM, independent engineering houses, or available special consultants in this area are used, the user must allow for review time and be prepared to accept responsibility for all the work to be completed. In this study, the majority of the reapplication studies were done inhouse, although on two occasions the services of an OEM were sought, along with an independent engineering contractor. This was done due to the inhouse workload and also to accommodate the timing of the projects that needed to be completed. Inhouse and outside work should always be broken down and separately evaluated for cost in the following categories:

- Aerodynamic-hydraulic work (performance)
- Mechanical design requirements
- Engineering drawings
- Fabrication of the parts
- Assembly and tests
- Inspection and quality assurance

Each of the above categories should have its own detailed workscope defined with clear goals and requirements. They should be stand-alone contracts with their own price breakouts. This gives all parties the opportunity to appraise and decide which is the best path to take. Even if all of the above is assigned to one engineering department or supplier, it provides better control of the work and the ability to follow the work and stay on schedule. An example where the control and schedule of such a project can be lost is in the area of the driver and driven equipment interface. Experience has shown that it is prudent to allow the main components to follow parallel, independent paths with the application engineer coordinating between parties. This will always leave the responsibility of the overall operation with the responsible engineer and, therefore, an "inhouse responsibility."

In matching the new requirements for the process, it is important to also update the equipment to take advantage of the latest state-of-the-art technology advancements of this type of machinery. Considerations must be given to vibration monitoring equipment, bearing temperature, instrumentation, overall control theory and hardware. This may include skidding the assembled unit. This may create a serious workload in the number of drawings required in the reapplication of this equipment. Considerations for fugitive emissions, seal technology, and overall maintainability must always be considered so that the unit is upgraded and updated during this operation. A useful analogy to remember is that the target or the gage post will always be to what quality would a new machine be specified. It is the challenge to the designer and the applications engineer to surpass the status of a new machine. The user should not settle for shop primer, for instance, just to cover the rough spots. Rather, it is wise to explicitly specify cleaning procedures, surface preparation, primer coat, and final coat details.

ENGINEERING REQUIREMENTS

In essence, all those tasks that are required in a normal capital project are needed, remembering that the target is a better job than a new piece of equipment. However, the job must proceed along those normal project lines along with the requirement of the additional engineering work that is normally done by an OEM. When the scope of work is defined, the original request for quotation (RFQ) document must be generated. In addition to the specifications, data sheets, and standard references, this document should include a mechanical flow diagram which is essentially a piping and instrument drawing (P&ID) for the major piece of equipment and all of its auxiliaries. In some cases where the decision is a close call whether to utilize new or refurbished equipment, this request for quotation document may actually be sent out to get quotations from vendors for new equipment. Hence, the requirements will be equally expressed and a bid tab evaluation will reveal the best alternative for the job.

When a purchase order is awarded, the RFQ must be finalized as a purchase order specification as if one were buying this apparatus from an OEM. Not only must this piece of equipment match the process performance requirements, it must also meet all the site standards and criteria for the particular job, and be in compliance with all national and local standards. The requirements are no less than generating a design that is basically state-of-the-art. All the normal engineering functions that must be performed with the purchase of new equipment must be done. In addition, all those items that the OEM provides must be generated by the project either inhouse or from an outside contractor or consultant.

The most important information is a clear understanding of the scope of supply and requirements. From this, individual workscopes for parts of the job should be generated so that individuals doing the engineering know specifically what must be done. After equipment has been selected a detailed list for the inspection of the equipment and the required modifications should be generated. A general arrangement drawing of the driver and driven equipment as well as all the minor individual items must be listed. The engineer may choose to have the whole assembly skidded by an individual fabrication shop or individual parts may go to the construction site for a stick built operation. All the drawings that are normally generated for the construction department must be generated for this equipment. Agreement must be clear with the engineering department guidelines as well as the operating division that will be receiving the equipment to satisfy all their respective requirements. The project will require documentation of exactly what is to be provided to know who is supplying what to the project and a purchase order specification allows all parties to know exactly where the interfaces lie.

As in any other project, the general arrangement drawings are the most important and must be finalized as soon as possible. Information for process connections as well as civil connections and utility connections must be finalized as soon as possible. This will include from foundation soleplates (anchor bolt location, unbalanced forces) up through utility usage quantities, flows, connections on the skid or the equipment, etc.

The development of the RFQ is based on the full anticipated redesign to make performance as well as modifications/repairs dictated by original inspection. It is prudent to request with the proposals an itemized list of parts/service pricing for those items that may need to be replaced at a later date following more detailed inspection and non-destructive testing. Such a request will allow the applications engineer to better evaluate the bids using this list to develop worst case scenarios. It also forces the bidder to list prices up front and, hence, avoid confrontation later, after the order has been awarded, when varying expert opinions commonly differ with regard to costs of repairs and when suddenly replacement part prices escalate.

As for the actual work categories, the aerodynamic or hydraulic performance of the machine can be done inhouse if the proper tools are available or this can be subbed-out to various suppliers, whether that be the OEM or other available firms. The mechanical design and rearrangement of equipment can be done inhouse, or this also could be subbed-out. The company was fortunate to do the majority of the work inhouse. Software tools that are required to do this are available to us in the company's central research and engineering center. The engineers can perform torsional and lateral critical studies and unbalance response diagrams. They also have the capability to do performance calculations and modifications for changes in speed, head, molecular weight, etc. A list of these programs that were utilized is shown in Table 1.

Table 1. Description of Machinery Programs.

COMPRESSOR PERFORMANCE	
CENTRAT	Centrifugal compressor calculations, curves
COMPRAT	Compressor stage calculations, power, head, temp.
BEARINGS	
DAMBRG	Stiffness and damping for pressure dam bearings
LUNDPARC	Stiffness and damping for partial arc fluid film bearings
PAPTLT	Stiffness and damping for tilting pad journal bearings
GEARS	
GEARATE	Strength and durability ratings of gears. API/AGMA
ROTOR DYNAMICS	
ROTBRG	Calculates bearing loads, prepares rotor/bearing data sets for use by rotor dynamics programs
ROTSTB	Damped lateral criticals, mode shapes, and stability of rotors on fluid film bearings.
TORCRHOL	Undamped torsional natural frequencies of a machinery rotor system (no branches) per Holzer
ULCRSP	Undamped lateral criticals of a flexible rotor on flexible supports.
UNBAL	Damped unbalance response of a flexible rotor on fluid film bearings.
FINITE ELEMENT ANALYSIS	
SAP5	Finite element analysis program, central to system. linear, 2-d and 3-d, static, dynamics, plotting.
GRIDPLOT	Plots input data file, reference and debugging
MOVEREP	Preprocessor for SAP5
MOVIDRAW	Plots SAP5 output with special effects
MOVISAP5	Translates output into geometry, displacement, stress, and temperatures
Others	Additional utilities for special effects graphics

Once the general arrangement drawing is reasonably agreed upon and internal modifications to the machine are underway, it is required that a design audit be completed on the machine. This involves the review of all sections of the equipment to be assured that under the new conditions stress levels are still within reasonable values. To do this, the engineer must consider any changes in speed or load on the equipment. The company utilized SAP5 finite element analyses on the impellers to ascertain if there were any problems due to increased speed or load on the wheels. Also, the interface of the wheels to the shaft must be reviewed along with shaft diameters and stresses. Going through the cross section of the equipment, all interfaces must also be reviewed for stress levels and stress risers for the new imposed loads. Coupling designs are reviewed and normally offer the opportunity to upgrade the quality of the equipment. In most of our cases, the retrofit would provide dry disc-type couplings or on some occasions due to studies of the torsionals with synchronous machines, the review for the possible application of a resilient coupling is required. Performing all the necessary engineering as if it was an original first-design creates quite a workload for the engineering staff. The engineer begins to realize what it really entails to come up with a brand new design. Normally the vast amount of engineering work and checking that the OEM must perform is not seen. If this work is done inhouse, all of these details must not only be completed inhouse but they must be reviewed, checked, and verified, and then an engineering package must be submitted with the original project files. The user is now designer of the machine, and carries the responsibility for its overall operations and compliance.

The generation of drawings gets to be a serious task. Not only must all those drawings be issued that are so freely requested of the OEM when purchasing a new machine, the engineering backup for those drawings must also be on file. The drawing packages submitted to the project must be timely and match in quality as if an OEM machine was being purchased. That is, during the machine's remanufacture, there must indeed be a review of materials of construction, joint designs, gasket designs, overall seal functions, stress limitations, and a record must be generated of all new parts and modifications that were made. Ultimately an instruction book must be generated. In the process of redesigning and applying the machine, the final drawing package will be more complete than any previously reviewed job. The user will have direct contact with all the calculations and design requirements of this machine that are not seen when the OEM does the job. The issuing of drawings is a difficult task and the instruction book is definitely the most challenging. Keep in mind that this task is driven by economics and the benchmark is a new machine. Therefore, the quality of the drawings and the updating of the machine in all its particular subsystems whether that be vibration probes, thermocouples in the bearings, new seal and/or coupling technology, or a proper lube and seal oil system, all of these details must be created. They must also be documented and have part numbers, so that the operating division has a method to acquire spare parts and have drawings adequate to allow inhouse or contracted service the of machine. There are times when this seems like an insurmountable task and the designer begins to question whether this was a good idea in the first place. If the economic review is done and the reapplied equipment competed against the OEMs and the designer still had a good case (i. e., justified by low evaluated bid), the company must proceed with this option. To prove that this is feasible, a series of machines and the approximate savings generated by reapplying these machines is listed in Table 2. Some were more difficult than others, but in all cases a considerable amount of cost was avoided since a new machine was not purchased. Despite the bottom line on avoided costs, the expediency in which many of these units were reapplied is the most remarkable. As an example, the ten megawatt condensing steam turbine generator set listed was identified and selected for relocation, disassembled from its original site, overhauled, rebuilt on a new foundation, and started up within six months. Hence, the project was completed for less than half the time and less than half the money when compared to a new unit.

TWO EXAMPLE CASE STUDIES

The examples which will be discussed are excerpted from the above list of machines that were reapplied. These are presented to underscore the effectiveness of this type of plan.

Example 1: Reaction and Process Change of a Cycle Gas Compressor

The cycle gas compressor in this example is a single-stage overhung barrel-type compressor design, DH3, with axial inlet and radial outlet. The original compressor gear and motor were used in a reaction cycle of the original process. However, the new application, although still a cycle gas compressor, is actually in the refining part of the same process. The application involved serious changes in molecular weight and the process con-

Table 2. List of Reapplied Equipment.

NEW USE	MFR.	MODEL	BHP (DRIVERS)	MAJOR BENEFIT	STATUS	REPL. COST MM$
OXIDE COMP.	CLARK	4M9-6 HQ		INC. CAP.	OP.	1.5
STM. TURBINE	WORTH.	1QS5	4,500	" "	"	1.0
CYCLE COMP.	I-R	CVS-30		INC. CAP.	PROJ.	0.8
GEAR	PHILA.	235 HSD		" "	"	0.5
CYCLE COMP. GEAR	PHILA.	235 HSD		MIN OUTAGE	SPARE	0.5
I.G.T.- TURBINE	G.E.	FRM. 5	17,650	MIN OUTAGE	SPARE	1.6
EXPANDER	DELAVAL	KJMV	7,700	" "	"	1.5
STM TURBINE	G.E.	DUY-125	2,000	" "	"	0.6
GEAR	G.E.			" "	"	0.5
BOOSTER A/C	I-R	MTA-752		" "	"	1.0
GENERATOR	G.E.	HL		" "	"	1.0
INTENSIVE MIXER	FARREL	11-D		INC. CAP.	OP.	0.5
MOTOR	LOUIS		1,200	" "	"	0.1
AMMONIA COMP.	WORTH.	BDC-54		INC. CAP.	PROJ.	0.4
MOTOR	E-M		400	" "	"	0.1
PLANT AIR COMP	JOY	TA-40		INC. CAP.	OP.	0.6
MOTOR	LOUIS		1,250	" "	"	0.1
PLANT AIR COMP	JOY	TA-40		INC. REL.	SPARE	0.6
MOTOR	TERRY	GSAA	1,160	" "	"	0.3
CYCLE GAS COMP.	A-C	DH3R		NEW UNIT	PROJ.	0.5
GEAR	LUFKIN			" "	"	0.1
MOTOR	LOUIS		1,750	" "	"	
H2 COMPRESSOR #1	WORTH.	BDC-4		NEW UNIT	PROJ.	0.4
MOTOR			1,250	" "	"	0.1
H2 COMPRESSOR #2	WORTH.	BDC-4		NEW UNIT	PROJ.	0.4
MOTOR			1,000	" "	"	0.1
20 MW GENERATOR	G.E.			RED. COSTS	OP.	1.6
GAS TURBINE	G.E.	FRM. 5	27,000	" "	"	1.5
GEAR	G.E.			" "	"	0.7
10 MW GENERATOR	G.E.			RED. COSTS	OP.	1.4
STM TURBINE	G.E.		13,400	" "	"	1.5
SUP. AIR COMP.	DEMAG	VK-63		INC. CAP.	PROJ.	0.8
MOTOR	E-M		8,000	" "	"	0.3
CYCLE COMP. TURB.	WORTH.	4Q	9,000	MIN OUTAGE	SPARE	1.0
OXIDE COMP.	CLARK	4M8-5HQ		INC. CAP.	FUTURE	1.5
#1 O2 P/L COMP.	WORTH.	BDC-B4		INC. CAP.	PROJ.	0.5
MOTOR	E-M		400	" "	"	0.1
#2 O2 P/L COMP.	WORTH.	BDC-B4		INC. CAP.	PROJ.	0.5
MOTOR	E-M		400	" "	"	0.1
PLANT AIR COMP.	JOY	TA-50		INC. CAP.	OP.	0.7
MOTOR			3,000	" "	"	0.2
CYCLE COMP. MTR	WESTNG.		14,000	INC. CAP.	PROJ.	0.5
CYCLE COMP. MTR	WESTNG.		14,000	MIN OUTAGE	SPARE	0.5
REFRG COMP DRVR	TERRY	GF-3	3,600	INC. REL.	PROJ.	0.8
#1 VENT REC. COMP.	COOPER	FM-3		NEW UNIT	OP.	0.4
MOTOR			400	" "	"	0.1
#2 VENT REC. COMP.	COOPER	FM-3		NEW UNIT	OP.	0.4
MOTOR			400	" "	"	0.1
48 ITEMS		BHP =	133,460		MM$ =	30.0

ditions. This is a difficult application. The designer finds that the change is so significant, that is, a reduction in molecular weight by about 50 percent which requires a significant increase in head which was accomplished by increasing the speed approximately 30 percent and by using a new wheel design. A comparison of the new and original data is in Table 3.

Simple fan law calculations would indicate that a speed change would gain the required performance, yet a more sophisticated review of this design showed that simply speeding it up would leave us running too close to the surge line. Therefore, a new wheel design was preferred. Interesting to note, the new wheel is the same diameter as the old wheel. However, to move out on the curve it was required to utilize the wheel with greater flow potential. This machine actually utilized the original motor, gearbox, and casing, yet substitution of the bull gear and pinion along with a new wheel got the performance map to match the process. The change in performance maps is indicated in Figure 2. This machine received all proper updates including the application of a mechanical dry gas seal. Various parts of this example were jobbed out; that is, the new gear set was fabricated by the OEM who manufactured the gear box. The box was sent to the OEM who installed the new gears with new probes and thermocouples in the bearings and shipped the completed gear box to the compressor OEM for mounting on the original baseplate. In this case, after the inhouse work was completed and designed, the project team elected to have the OEM of the compressor supply the wheel and install it in the machine with the dry seal design system that were specified as part of the drawings for the project. The original motor was overhauled and reapplied, even though it is oversized. A cross section of the machine is shown in Figure 3 as modified.

Table 3. Comparison of Old vs *Performance for Case Study Example 1.*

ITEM	CASE DESCRIPTION	
	ORIGINAL DESIGN	RERATED DESIGN
Molecular Weight	21.8	11.3
Compressor Speed	8385 RPM	10,985 RPM
Brake Horsepower	1570	830
Polytropic Head	13,400 FT.	18,000 FT.
Gas "K" Value	1.255	1.385
Suction Pressure	212.7 PSIA	139.7 PSIA
Suction Temperature	104 F	104 F
Discharge Pressure	284.7 PSIA	174.7 PSIA
Inlet Flow	3745 ACFM	3667 ACFM
Wheel Diameter	21.5"	21.5"

Additionally, the new process required very low molecular weight application for hydrogenation of the catalyst. In order to meet all the particular requirements of this job (several off-

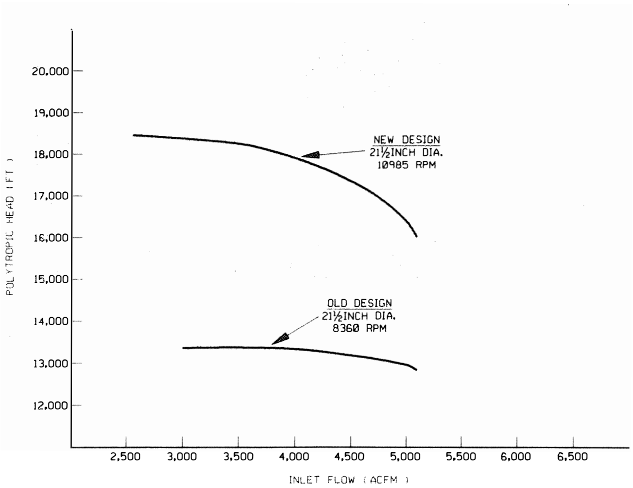

Figure 2. Performance Curve of Case Study Example 1 Before and After Modification.

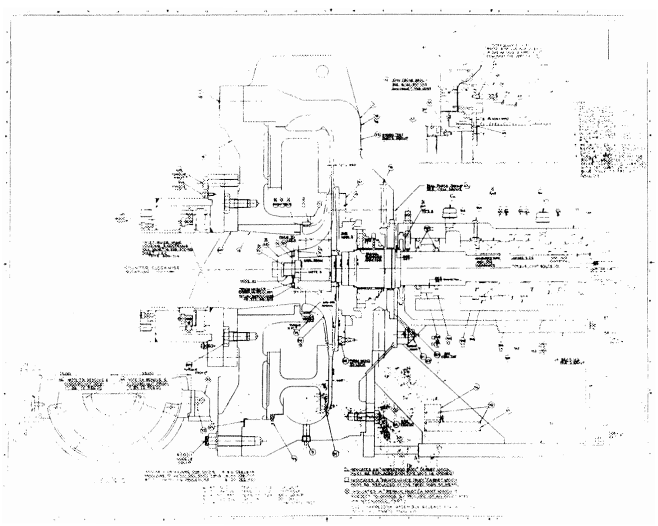

Figure 3. Cross Section of Compressor After Modification.

design cases), the engineers chose to utilize variable inlet guide vanes for improved control over the operating range. This machine is now performing properly and actually has surpassed all of the goals and those of engineering in the project along with the operating department. In finalizing the engineering on this machine, a borderline design was purposely not chosen. The original wheel could have been utilized, but based on experience, this particular process is expected to expand in the future and, therefore, the larger capacity wheel and the inlet guide vanes were chosen. This has proven to be a good decision, because upon startup, it was found that the system resistance curve had reasonable error in it, and in order to run at an efficient point in the performance map with the motor drive, the guide vanes certainly turned out to be a worthy addition. Refer to Figures 4 and 5 for a comparison of the compressor train before and after modifications.

Example 2: Capacity and Horsepower Increase of a Cycle Gas Compressor System

Again, the compressor in question is similar to that discussed in the previous example, i.e., a single-stage overhung impeller design (CVS30). However, the compressor casing is a stainless steel casting and components in contact with the process are also

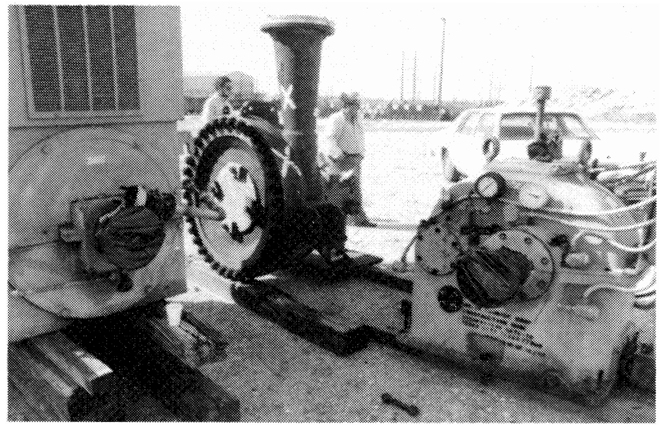

Figure 4. DH3 Compressor with Motor and Gear Prior to Revamp.

stainless steel. A new compressor to meet the process requirement is, needless to say, a very expensive machine with standard delivery in excess of one year. The cost of this conversion as compared to the cost of a new compressor only, on a percentage basis is less than 15 percent. Likewise, by refurbishing an existing gearbox, a savings of 70 to 80 percent in time and cost of a new unit is possible.

This particular compressor is one of five in similar service. The compressor was relocated from a facility that was shutdown due to local economic conditions. Originally, the compressor like its cousins, was steam turbine driven but in the new application, at the new location, having a variable speed driver was not feasible.

The actual process parameters for this machine did not change significantly, but the opportunity was utilized to run the machine at higher flow rates, speeds, and at a more efficient point. Refer to Table 4 for comparison of old *vs* new performance and to Figure 6 for performance curves. This was of particular importance because it required the compressor to be motor-driven. In order to get the required speed, this application needed a gear box, and so an available gear from the same location (another unit) was utilized in addition to the compressor. Also, a lube system was required so the sweep was completed and a lube console was used from yet a third unit in the plant. The horsepower of this machine for the new application was almost double the original design. A new motor was purchased due to the unavailability of a motor, yet the reutilization of an existing

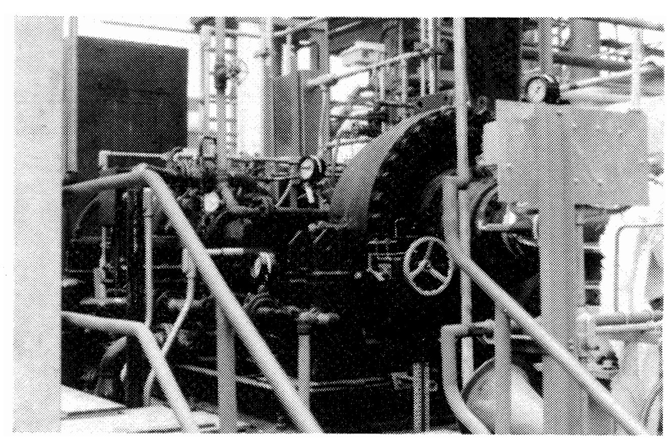

Figure 5. DH3 Compressor System in Operation Following Modifications.

Table 4. Comparison of Old vs New Performance for Case Study Example 2.

ITEM	CASE DESCRIPTION ORIGINAL DESIGN	RERATED DESIGN
Compressor Speed	4140 RPM	4523 RPM
Brake Horsepower	7830	10640
Wheel Diameter	35.5"	32.0"
Inlet Flow	28.5 MMSCFH	37.8 MMSCFH
Molecular Weight	29.0	30.0
Polytropic Head	6,400 FT.	5,670 FT.
Gas "K" Value	1.350	1.375
Suction Pressure	260.7 PSIA	278.6 PSIA
Suction Temperature	11[illegible] C	31.6 C
Discharge Pressure	310.7 PSIA	340.0 PSIA

gear box and a compressor turned out to be very fruitful, both in overall cost and project schedule. (*NOTE:* A surplus motor was actually found within the corporation at a separate location, but due to an even more serious emergency outage condition, the motor was taken and used by another division!)

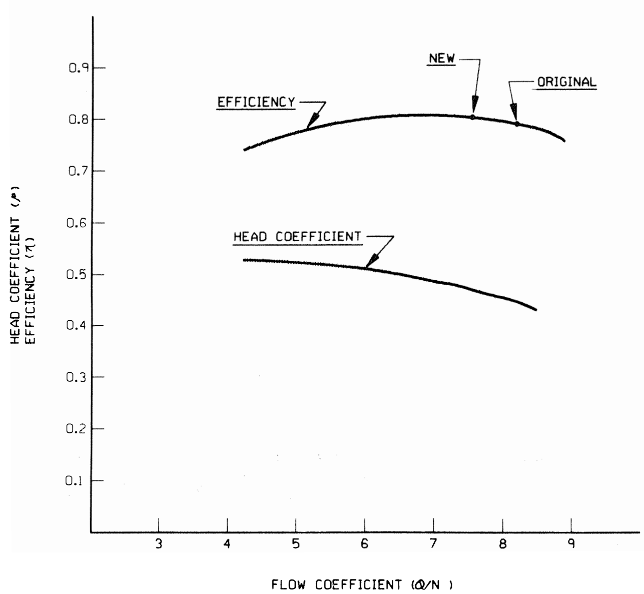

Figure 6. Performance Curve of Case Study Example 2.

The compressor required wheel investigations, wheel-to-shaft stress analyses, a review of the growth or movement of the wheel due to both new centrifugal forces and to the load imposed from the impeller on the shaft and the centrifugal and the gas forces on the impeller. This was done using finite element analysis, SAP5, for which a typical output can be seen in Figure 7.

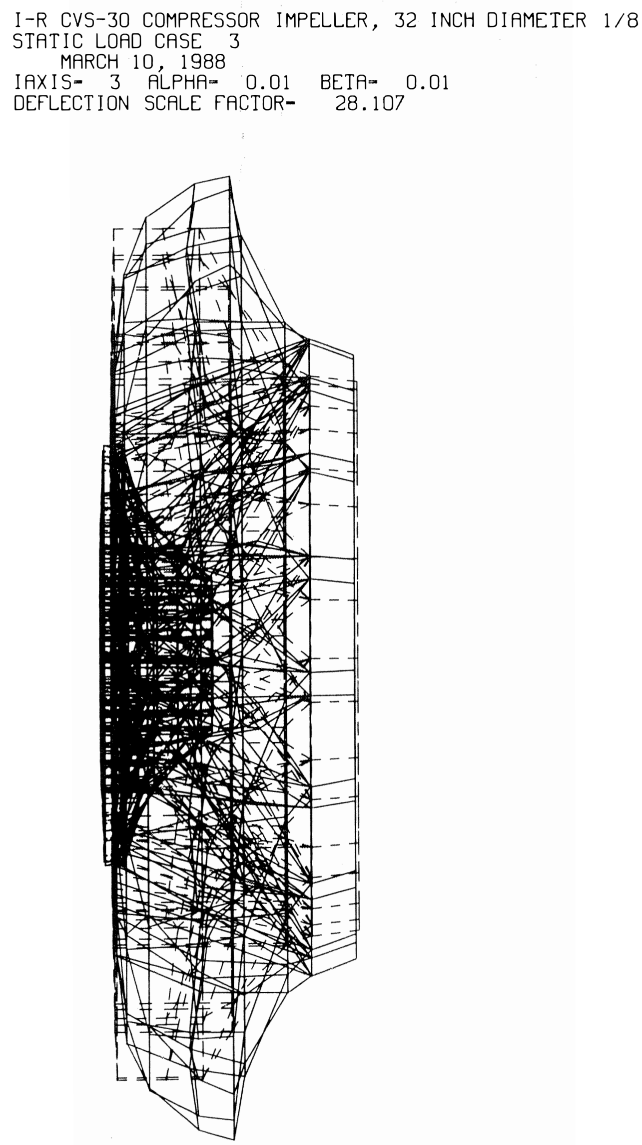

Figure 7. Finite Element Analysis of Modified Impeller.

Due to the higher horsepower requirements of this machine, a new shaft needed to be designed and manufactured with larger diameters. This even forced the requirements of a larger diameter bearing for the outboard bearing of the compressor. The design of this bearing and its associated seals was done inhouse. Yet the parts were fabricated from an outside supplier. In both of these cases, all the required engineering and drawings were generated by the project. As far as the project and the operating division were concerned, they were basically getting a "brand new" machine with all the normal drawings and the instruction books typically provided by an OEM. Many of the changes that were required involved serious engineering calculations. Coupling designs were reviewed, new couplings were specified and purchased, bolting designs were reviewed, and overall stress levels were reviewed to be sure that we were well within reasonable values. As can be seen in the cutaway outline (Figure 8), it was required to utilize an elastomeric coupling due to the synchronous motor drive on this machine. The whole system was reviewed for torsional and lateral vibrations and all loading throughout the system, including the gear box. The gear box was of no concern, because its original rating was much higher than those that would be applied even during startup. Nevertheless, a gear rating analysis was completed per the latest API and AGMA standards to complete the engineering design calculation package.

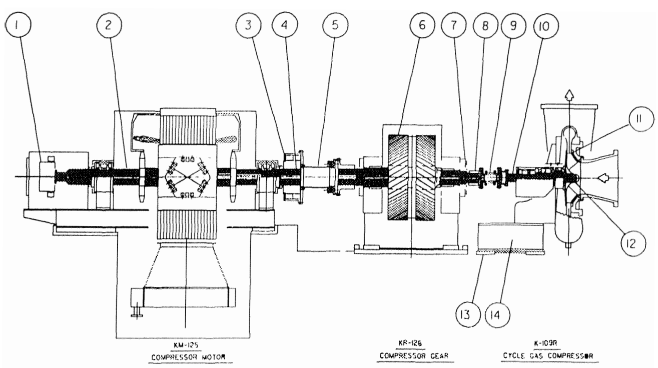

Figure 8. Cross Sectional Layout of CVS-30 Drive System, Design Audit Included: 1) synchronous motor and startup considerations, 2) motor lateral critical speeds, 3) system torsional study, 4) coupling interface (torque capabilities, stresses), 5) LS coupling selection, 6) gear strength and durability rating, 7) shaft seal modifications, 8) keyway analysis, 9) HS coupling selection, 10) shaft and bearing redesign, 11) impeller modifications (efficiency gain, speed increase, FEA), 12) impeller/shaft interface, 13) soleplate design, 14) baseplate modifications.

The primary component of this redesign was of a mechanical nature. The loading of the shafts, the horsepower transmitted, and all those considerations from wheel deformations due to increased speed, or centrifugal forces and impeller induced loads, along with a review of excitation of the impeller and its vanes, were reviewed. The original impeller was subjected to shaker tests (see Figure 9) to be sure that there was no coincidence of any known excitation frequencies throughout the system. The actual wheel utilized was also run through shaker tests in its final state (i. e., diameter change). The interface of the wheel and the keyway was also of concern and had specific engineering modifications done to the design. The shaft was also thoroughly reviewed and, as noted, required an increase in diameter at the small bearing, and at the impeller interface. Also, an integrally forged hub was utilized to avoid any problems in that area.

As mentioned earlier, the importance of inspection is paramount. Upon disassembly of the compressor, the casing was NDT'd, and several cracks were found in the diffuser vanes, as can be seen in Figure 10. These were weld repaired after material verification through analysis and thorough discussion with the materials engineers in developing appropriate weld repair procedures. The high speed coupling and the low speed coupling were both reviewed, analyzed, and optimized. The speed increasing gear required a rotation change and an overhaul. Vibration probes were updated and bearings were retrofitted with thermocouples. The lube oil console was totally rebuilt and modified for the new requirements. The original console had seal oil appurtenances which were no longer required, for example.

Figure 9. Impeller Shaker Test.

Figure 10. Diffuser Cracks.

Hence, the result is the marriage of three old machines in a new system of excellent design utilizing the latest state-of-the-art equipment. A photo of the compressor before and after redesign is shown in Figure 11 and 12.

All of the above information, calculations, and audit is included in a file retained by the project and, on record—the user company is the OEM. This is all required if one intends to perform this sort of work. It is a very difficult task whether it is done inhouse or it is "jobbed out." But, as long as the designer is will-

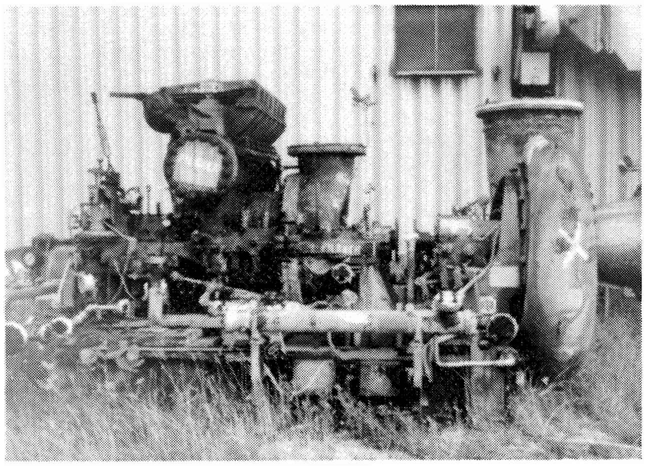

Figure 11. CVS-30 Compressor Before Modification.

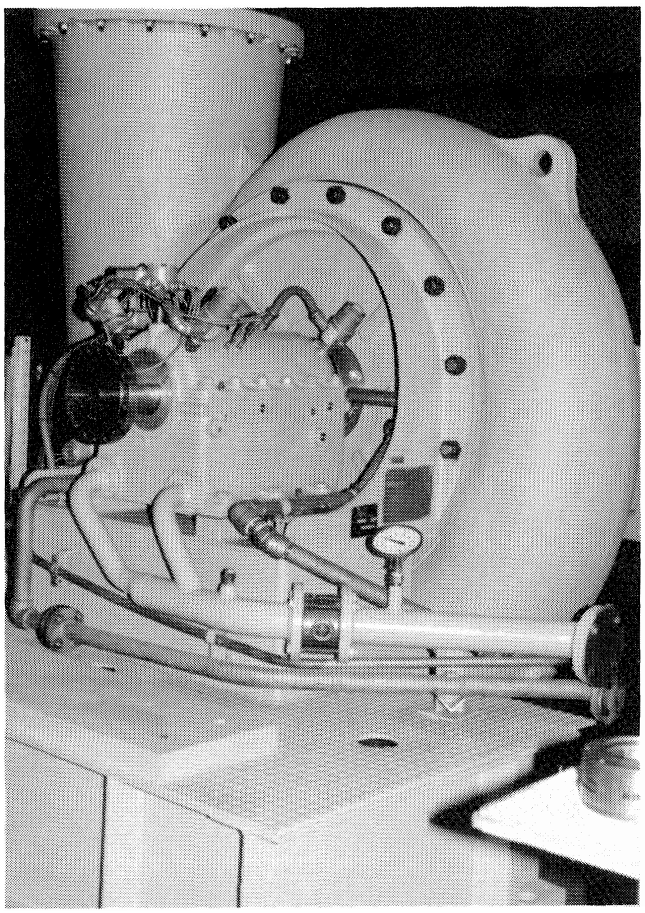

Figure 12. CVS-30 Compressor After Refurbishing.

ing to expend the additional engineering man hours and thoroughly audit the system, the rewards and justification will undoubtedly be realized.

SUMMARY

To summarize, machinery reapplication requires the commitment to utilize the available knowledge and talent inhouse or obtain it elsewhere to perform a proper review of all the various components. The engineer responsible for the total job requirements must familiarize himself with the many areas of concern that need to be addressed when applying or reapplying machinery. Below is a listing of typical national standards which represents those areas which the engineer must be familiar with when working with machinery. These standards should be utilized for compliance with applicable codes.

AGMA	ASME	ISO	NSPS
ANSI	ASMI	NEC	OSHA
ANST	ASTM	NEMA	
API	AWS	NFPA	

It has been our goal to expose what can be accomplished and to touch on some of the subjects that need to be addressed when a serious reapplication is under consideration. Any reapplication that involves changes to the equipment or serious aerodynamic changes will require a full review of the machine that must include torsional and lateral rotor analyses as well as possible problems in loading, thrust, balance piston, etc. Some applications may be very simple and others require an absolute indepth study of all the components. It may seem like a lot of extra work and time spent, but it is the only way to gain some assurance that the apparatus when it is placed in service will perform properly and, thus, minimize the risks that the user is trying to avoid. It should be remembered at all times that the benchmark or goal is to match or surpass what the client would be anticipating in a new machine to fulfill the requirements of the task at hand.