INSTALLATION OF LARGE ROTATING EQUIPMENT SYSTEMS — A CONTRACTOR'S COMMENTS

by

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ABSTRACT

The profitability, reliability and maintenance of gas turbine driven centrifugal compressor units are not inherent with the machinery, but for the most part, depend on the piping system to which they are connected and the careful testing, installation, and initial operation of the units.

Contractors are responsible for the proper interfacing of the compressors with the associated process conditions, foundation, piping, electrical and control systems. The gas turbine driver merely maintains the rotating speed of the compressor in a predetermined manner. Usually, the rotating equipment system is custom designed for a unique application and this precludes any so called standard procedures. Each system must be carefully reviewed prior to selecting the design point of the compressor to provide flexibility of operation and include allowance for off design performance. This, before the fact decision, is a source of many controversies because few process designers really appreciated that when the design point of the compressor system is established, the machinery then becomes the constraint on how the process will operate. The critical design problems then center on how to operate the process without damaging the rotating equipment.

There is a lot of discussion on how to align rotating equipment. We place great emphasis on how the equipment is aligned the first time. Our belief is that the equipment should be more out of alignment the first time it is placed in operation than at any other time. The basic reason for alignment is that thermal gradients change during the loading of the system. We realize that this first alignment is a judgement and request that all concerned approve the procedures. The thermal center of the system is located and all movements are predicted from this location. It is important that this location be fixed so that the machinery will return to a known position during shut down.

INTRODUCTION

The development of the large horsepower industrial gas turbines and the acceptance of the aircraft derivative gas generator with associated power turbine created some new opportunities in the gas processing industry. Power is available in large quantities from a single machine. This single power source can produce a reliable and simple operating plant or an extremely costly situation if design deficiencies, installation errors or improper start-up procedures are encountered. As an engineering and construction organization or contractor, we have been associated with all of the above and this paper is based on some of our experiences with gas turbine driven centrifugal compressor systems.

ROTATING EQUIPMENT SYSTEM

The process engineer usually determines the desired flow, pressure, and temperature environment for the compressor by considering data as it is understood at the contractural meeting. Based on the assumption that these data will not differ significantly from the conditions at contract completion, a judgement is made on the design point for a compressor. This is the basis of design used by the compressor manufacturer and is usually the performance guarantee point for the process. Given the design point, the compressor manufacturer offers the machine believed to be the most efficient and reliable for the application and predicts the rotating speed and power requirements using direct coupled compressors, gear driven units or a combination of both.

The speed and power requirements are used as guides in determining the gas turbine selection. When the gas turbine is selected a review of the entire system is proper to insure efficient use of fuel, varying process requirements and costs. After this is done, the performance of the system is fixed. It will operate only within the boundaries established by the performance characteristics of the machinery. A control system is designed to maintain these boundaries or to shut down the process or compressor train whenever required. This operating zone is illustrated in Figure 1. It was prepared to partially describe an offshore compressor station operation by assuming constant suction conditions at the compressor. When this is done the compressor system curves can be plotted using discharge pressure and inlet flow.

Figure 1 is a graphical representation of the process and mechanical interactions between the compression facilities and pipeline hydraulics of an oil associated gas gathering system.

A brief explanation of the facilities involved in this project is in order so that a full understanding of Figure 1 will precipitate. The facilities in the gas gathering program consist of a series of independent gas-oil separator platforms producing the associated gas into a number of subsea gas gathering lines which terminate at a centralized gas compression location. Gas turbine driven centrifugal compressors are used so that deliv-

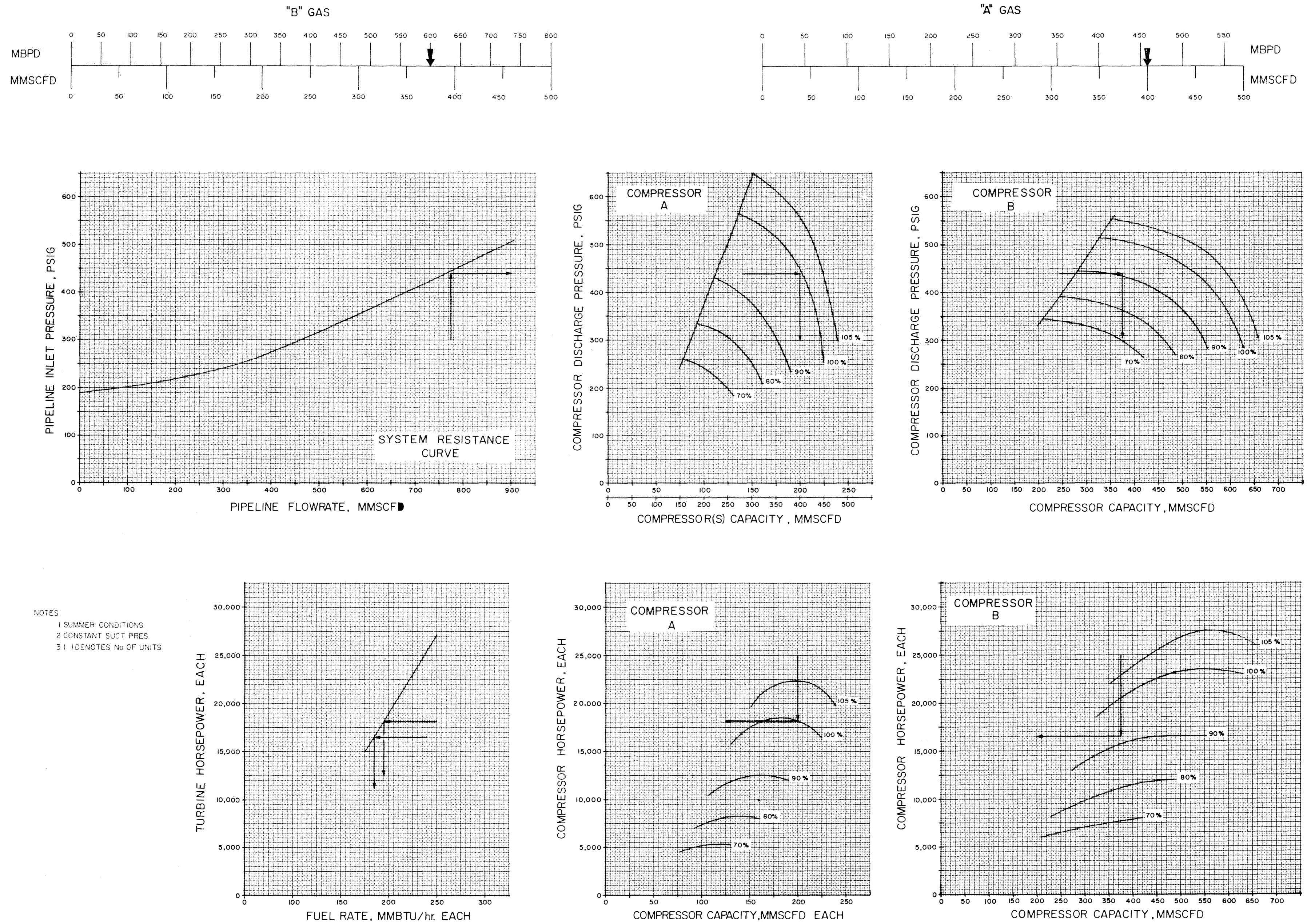

Figure 1. Compressor Performance Map.

ery of the gas at a constant pressure will be achieved via a subsea pipeline to the delivery point. This may be achieved by varying the compressor speed (turbine speed) as the frictional resistance in the delivery line varies with gas throughput. In an effort to predict the required compressor performance as well as the system limitations, Figure 1 was created. The two nomograph scales appearing atop Figure 1 represents the oil production and associated gas volumes determined by a scalar multiplier known as the gas oil ratio. Two independent production horizons may be produced in the oil field in any proportions with the gas taken to be cumulative.

The system resistance curve plotted at the mid-left position of Figure 1 represents a series of pipeline hydraulics calculations at varying gas volumes (and calculated corresponding required pipeline inlet pressures) assuming the intensive gas data is constant in the delivery line. The static delivery pressure requirement of 180 psig can be attributed to frictional resistance in the delivery pipeline. The two typical centrifugal compressor capacity vs. pressure curves illustrated in the center of Figure 1 represent two compressor services which will be employed to impart the necessary energy into the gas at the compression location. Two different compressor services are being contemplated at the compression location with multiple identical units per service. Each of the two compressor services have characteristic capacity vs. pressure curves and multiple units of the same characteristic can be represented by merely modifying the capacity scale by a multiplier corresponding to the number of operating units. Compressor A shown on Figure 1 will consist of a maximum of two operating units and compressor B will consist of a single unit.

Located directly below the compressor characteristic curves are the corresponding horsepower requirements for the compressors. These curves when used in conjunction with the capacity vs. pressure curves will effectively demonstrate the horsepower requirements per compressor in terms of compressor speed and capacity. Additionally, the turbine driven fuel rate in MMBTU/HR may be determined by comparing the compressor horsepower requirements (Per Unit) with the turbine horsepower and the fuel consumption plot in the lower left corner of Figure 1.

The intent of this figure is to demonstrate graphically the physical and mechanical limitations of a given system configuration. This concept of representing the system has been effectively used to choose compression equipment, design compressor control systems and predict system efficiency and limitations. By replacing the compressor characteristic curves with a different manufacturers curve, altering the gas flow rates to the compressors, or by changing pipeline sizes we can determine system response at steady state conditions and consider optimum designs. From this type operational data the mechanical design of the power train can be considered and an operating zone established.

It is very important to reach agreement on this operating zone before the purchase orders are signed and unit responsibility is assumed.

UNIT RESPONSIBILITY

The most controversial area is in unit responsibility. What is it? Who should have it?

Unit responsibility, to us, means the responsibility for coordinating and approving all the factors necessary to provide an installation that will operate and perform to contractural agreement. This just doesn't happen; it has to be made to happen. It can not be known until the unit is operating under plant conditions. Careful and precise assignment of this responsibility is mandatory. The equipment selection, design and construction procedures depend on the interpretation given to unit responsibility.

As a contractor we must, through necessity, be able to function when we do not have unit responsibility, but we make an effort at coordination meetings to clarify our position. Unit responsibility is not just conducting the rotor response studies and advising when difficulties occur. It is a commitment to participate in the complete engineering of the turbine compressor system.

THE INSTALLATION OF THE ROTATING EQUIPMENT SYSTEM

As a contractor, we usually design the foundation and piping system for the compressor train. This interfacing with the compressor train is covered during the coordination meeting to minimize disagreements during construction. The goals are to connect the compressor and piping so that the forces and moments transferred between them will not be excessive, and to connect the gas turbine and compressor skids so that alignment procedures can be reached.

Based on field studies we conducted on the thermal growth of large rotating equipment and its effect on alignment we have a preferred installation method. Consider that a steel beam 10 feet in length will expand about 40 mils during a 50°F change in temperature. This is 70° to 120°F or 70°F to 20°F and is typical of many areas. Many compressor skids are about 10 feet in width and even greater in length. Consider a gas turbine skid 10 feet wide and 40 feet long. A 50 degree change would cause a 40 mil change in width and a 160 mil change in length.

These thermal growths occur and are many times the precision used during alignment with dial indicators or optical methods. Another consideration is thermal gradients through beams. Consider a simply supported beam 10 feet long with a 100°F difference in temperature from top to bottom. It will deflect 112 mils at midpoint and would require 18,418 lb. force at midpoint to produce a counter deflection. This force on a 1″ diameter bolt 6″ in length would produce a stress of 23,000 psi and this would cause the bolt to elongate 5 mils.

This example is to call attention to the fact that one should prevent these thermal growths or to let them take place in an ordered way than to make assumptions that they are not critical. We recommend establishing a thermal center for each skid and then fixing this center to the foundation so that all horizontal and longitudinal growths can be maintained and referenced from that point. A key is supplied so that the longitudinal growth is ordered.

Notice from Figure 2 the location of the fixed points for the turbine and compressor and the key guides. The other points are anchor bolted sole plate locations. These are for vertical support only and are not torqued enough to limit thermal expansion in the horizontal plane. There must be adequate radial clearance between all anchor bolts and the holes in the skid to allow for this growth.

Careful consideration is given to the moments and forces transmitted to the foundation through the compressor nozzles and base. These forces rarely cause problems if the field piping is installed as it was designed during the piping flexibility study. However, little consideration is given to the moments and forces transferred to the foundation and skid to skid by the lube oil supply and return oil headers. We prefer that each vendor provide for this by assuming that the point of juncture

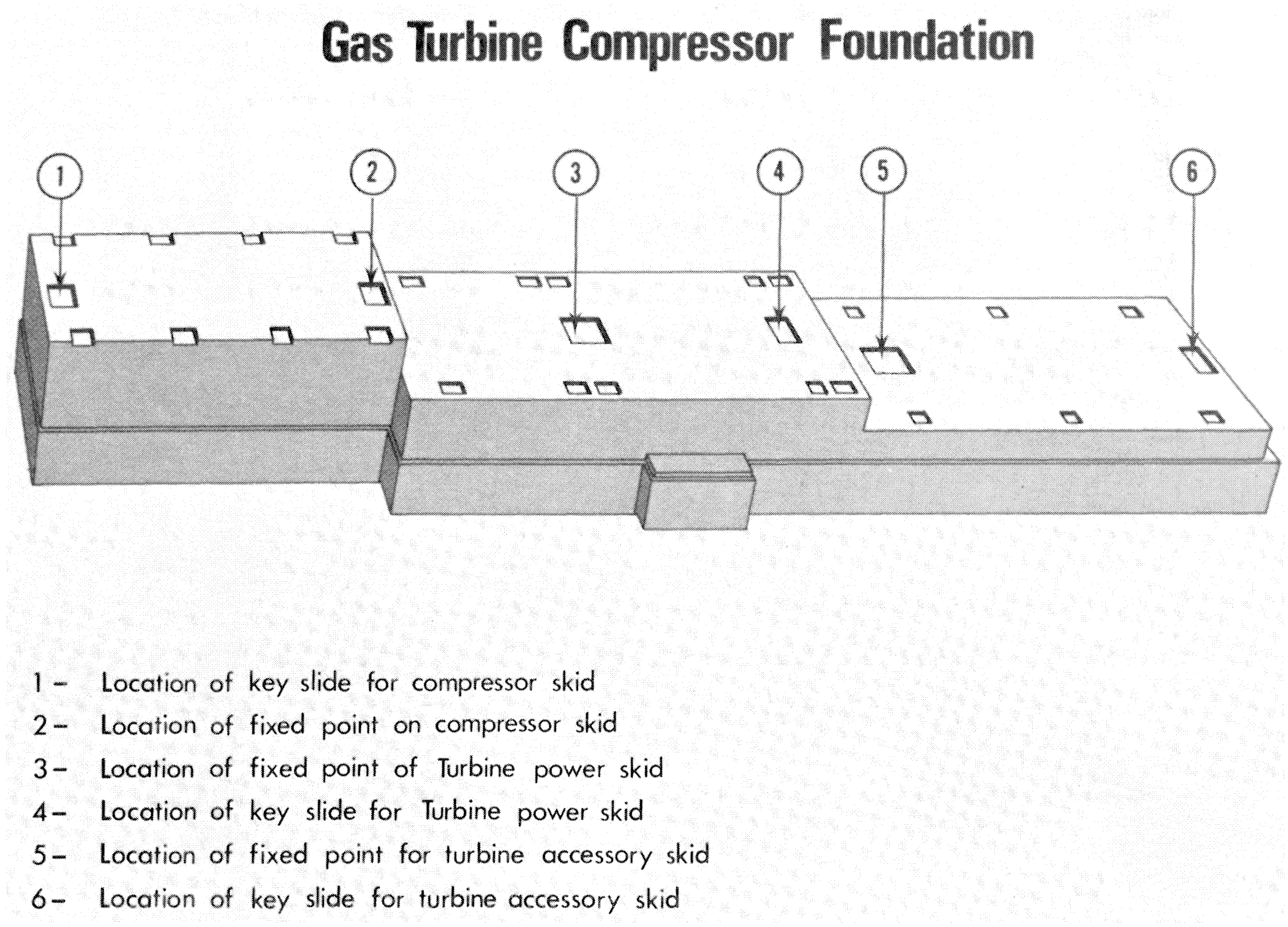

Figure 2. Gas Turbine Compressor Foundation.

between skids be a thermal center; i.e., does not change location with temperature. This usually means the installation of expansion joints in these lines, especially the larger oil return lines. It is mandatory when a gear is in the system having a common oil supply furnished from a separate unit.

THE BASIS FOR ALIGNMENT

The vertical growth of each part is reviewed with each vendor. The thermal gradients in the support legs, gear, turbine and base plate support are discussed and agreed upon. An alignment drawing is prepared reflecting this agreement. It is a judgement and the initial cold offset alignment both horizontal and vertical should be the greatest misalignment the machines encounter. During design load operating conditions when the thermal gradients are steady, the alignment should be well within acceptable limits.

To illustrate how slight changes in alignment can influence the performance of machinery consider the following example.

A gas turbine, compressor, gear and compressor train was placed in successful operation. After a year or so the train was shut down for inspection and maintenance. During restart it was noticed that the compressor shaft directly connected to the gas turbine was vibrating at a frequency less than rotational speed. This was unexpected because the machine had operated satisfactorily for a long time. We were fortunate that the client had installed X-Y probes in the machine and we could obtain the orbit shown in Figure 3. We were given permission to change the alignment of this machine while it was loaded. The turbine is about 20,000 hp. This was done by installing electric heaters on the support legs of the compressor. The gradual heating of these legs resulted in changing the orbit as shown in Figure 4 and Figure 5. Notice that the rotor became stable. This deliberate misalignment caused an increase in bearing load and produced a more stable condition.

It was vibrating at once per revolution frequency as it had done previously. The machine was operated with the heaters attached. During a subsequent shut down it was noticed that the upper half of the bearing had been installed with the pressure dam on the opposite side of 180° from the previous position. When the bearing was installed properly the shaft was stable again and the oil whirl or instability could not be observed. One end of the machine was raised about 15 mils as a result of heating legs approximately 80°F. This experience gave us confidence in aligning machines while they are fully loaded and operating at design conditions. We are considering using a device (1) such as the one illustrated in Figure 6.

We plan to install these between the foundation and machine support base at each anchor bolt location and use them for positioning the skid relative the foundation. The device permits horizontal movement independent of vertical movement. We believe this may be an advantage especially in offshore application of large trains with rotating shaft up to 100 feet in length. These would be permanently mounted devices.

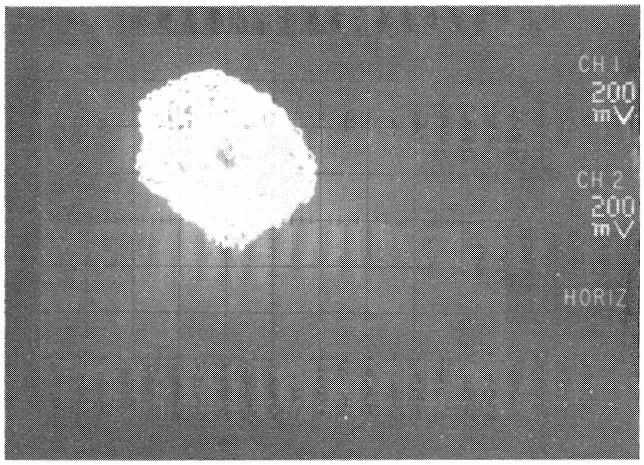

Figure 3. Orbit Before Heating Supports.

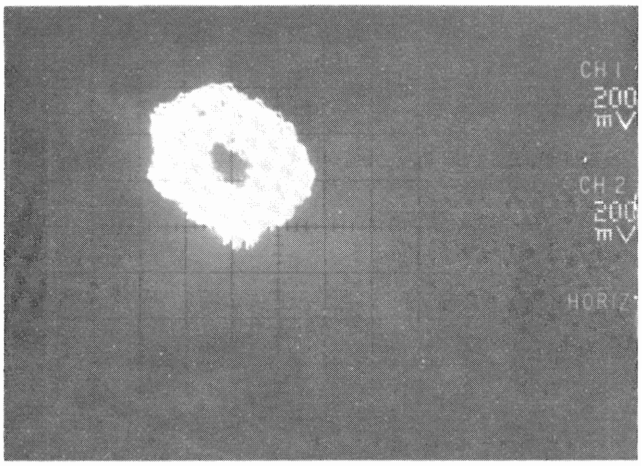

Figure 4. Orbit During Heating of Supports.

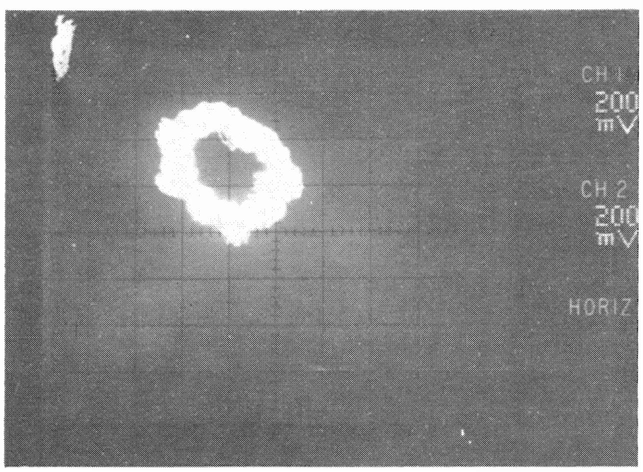

Figure 5. Orbit After Heating Supports.

With proper instrumentation and data analysis techniques the effects of small movements of the base could be observed under actual operating conditions. We can maintain symmetrical horizontal growth and ordered axial growth of the skid with the dowel pin, and key and slot arrangement. We could then determine how sensitive the train was to vertical growth by moving the base up or down as required.

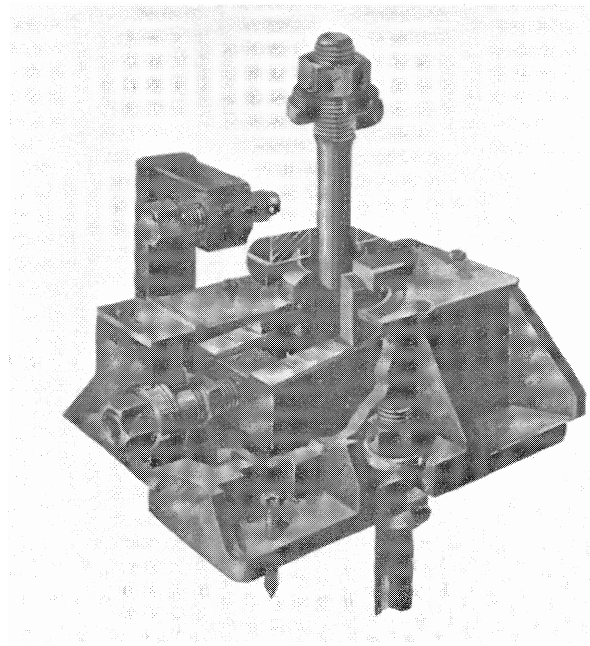

Figure 6. A Device to Provide for Horizontal and Vertical Movement.

In critical conditions we recommend that the support bases be maintained at a constant temperature by using the lube oil of the system. This is kept at about 120°F independent of load and changes or gradual. Routing this oil through the support legs would keep them at a constant temperature independent of the load. We have used this in 16,000 horsepower electric motor driven crude pumping units. A variable speed drive unit is installed between motor and pump to permit changes in pumping rates and to minimize chances for hydraulic shock. The motors can operate loaded or unloaded. With the oil circulating through the bearing supports of the motor the vertical growth is known and can be matched with the oil cooled variable speed drive unit. These units were operated and no changes were required in the calculated settings. The aligning of power trains under load is being done and is receiving more attention as more instrumentation is developed. (2)

This controlled temperature concept is being considered for offshore applications to avoid possible difficulty with random expansion due to radiant heat and from changing weather conditions. It is mandatory to consider the growth of these steel platforms with temperature changes and it is especially important to consider the effect of this growth on the alignment of the compressor trains. These thermal movements are as important as wave induced motion.

THE SURGE CONTROL

Except for damage due to solid objects and liquid slugs, surging of the compressor, or more important, preventing the surging from happening receives great attention. It is accomplished by passing flow from discharge to suction. The discussions usually concentrate on just exactly when this bypassing is necessary, absolutely necessary, or desirable.

Some people become very interested in how much enegry can be saved by operating a compressor system as close to surge as possible. We advise our clients not to worry about this until the plant has operated for some time and operators are familiar with and have confidence in the equipment.

At that time tests can be conducted to more accurately predict the surge characteristics of the system. More energy can be saved by playing it safe until the situation is well in hand. The machinery manufacturers are well aware of the difficulties of surge and their advice should be considered, especially during the initial operation of the system. A simple low flow alarm, and or minimum flow bypass arrangement is usually sufficient during start-up.

Depending on location and staffing of the plant, a complete automatic surge control system may be practical especially in high energy, high pressure application. If it is expected that the gas flow to the plant may be lower than predicted it may be mandatory to install a valve outside the surge control loop so that the plant can be operated with existing compressor system and prevent the stonewall effect. This will establish an operating point within the surge control loop and the surge controller would be functional.

THE INSTALLATION OF GEARS

If we could select a gear, install it in a flat rigid foundation, supply it with clean, cool oil, align other equipment to it and then complete the other facilities, it would be great. Unprofitable, but great. We prefer to mount gears on a separate concrete foundation that is an integral part of the continuous foundation structure. However, there are successful installations where the gear is mounted on a common steel base with the driven equipment. If this is the preferred arrangement, special care must be given to support structure of the gear. It should be approved by the gear manufacturer prior to shipping the skid. The method of attaching the gear to the base and base to the foundation should be completely understood prior to the final rotor response study. We learned that it requires personal attention to get this done. It may be that people that do these studies have a very limited field experience with their equipment or that management is so naive to believe that field experience is no longer required.

THE MAKING OF A SUCCESSFUL INSTALLATION

We are most successful when the field installation supervisor participates in the factory testing of the equipment that he personally will install. We recommend that he be present even if we have to pay for this service. For whatever reason, the people selling the equipment are not as concerned with a successful installation as we sometimes believe they should be.

We prefer to do business with manufacturers that are available from conception to successful completion of a project than those that are so well organized that it takes three or four days or longer to get their attention. We meet with the manufacturers when our design drawings are complete and ask if they have any objection to the method of installation and operation of their equipment.

THERE WILL BE NO PROBLEMS

How many times have you heard this one? It is not a bad sentence and of course you will never get anything built competitively if excellence is the goal. Equally important is having a procedure agreed upon at the initial coordination meeting on what will happen if an unexpected problem occurs. We raise the question and expect the manufacturer to give us full cooperation in their answer. What outside consultants do they use to assist them in defining and solving problems?

We define and make clear that our capability is terminally committed to our clients. We also outline our position in the event the manufacturer does not cooperate. We only know what we measure and we are prepared to measure and record vibrations and pressure pulsations during start-up and operation. We also know that we can measure a lot more than we can explain and from experience we believe others are in the same position. If it becomes our responsibility to obtain more detailed and state of the art diagnostic data, we contact our field data specialists. We have associated with them for years and know what they can do for us. They have good equipment and are experienced in taking field data. Our approach to a field problem is to determine if there is an error in skill or installation, if a quality control problem exists, or if a design error occurred. The latter being undesirable.

A CASE HISTORY WHEN EVERYTHING WENT WRONG

We were awarded a contract to design and construct a plant to process 900 MMSCF/D of gas and make natural gas liquids consisting of ethane and heavier components as a product. (3) This is something we do well and most all of the aforementioned topics were included in the project; i.e., total interaction with the manufacturers and client. Then fate or Murphy's Law began to appear. The fuel gas valve of the gas turbine was tagged correctly but had the wrong plug installed. The jack shaft in the gas turbine was adequate at 3,600 rpm but not at 5,000 rpm, the design speed. The compressor had a rub during initial operation and a new shaft and slightly modified interstage seal was required. These occurred in the field after factory tests were conducted. The complete unit was not tested because of its size and the delay in construction schedules prevented a test of this type. An identical steam turbine driven compressor train utilizing the waste heat from the gas turbine also gave trouble. We had to field balance the steam turbine because the coupling was improperly installed during the field assembly. The steam turbine compressor had a similar rubbing problem and was modified. These mechanical problems were solved and we started the turbo expander. This expander was one of the largest built at the time and some diffuser vanes were mechanically resonant at design conditions and failed. The plant piping vibrated because of flow induced vibrations. These problems were solved and the plant performed satisfactorily. My main point in telling this story is that if we had not been prepared to diagnose and solve these problems as they occurred with our equipment manufacturers on a professional basis we would have had a most unpleasant experience. The field service personnel of the compressor, turbine, and turbo expander manufacturers gave outstanding performances and cooperated fully with us in solving problems.

It was a pleasure for me to see a member of the gas turbine sales organization assisting with field problems. We, the client, and all rotating equipment manufacturers are very proud of the manner in which the problems were solved.

During the 8,000 hr. inspection of the gas turbine there were no changes made in the alignment of the turbine to compressor. This unit was installed with the key slot arrangement and contained expansion joints in the oil return header.

CLOSURE

We have offered some comments on the installation of large power trains and suggested some ideas that may be of interest to you or that you may be including in your organizations at the present time. It is the intent of this paper to indicate that clients, equipment vendors, contractors, operation and maintenance people should work together as a team to produce the desired result. This is especially important when unexpected problems arise during the start-up of a plant. In our organization we are organized not only to conduct the problems of business but are prepared to participate in the business of problems.

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