USING TEAM AND FAULT TREE ANALYSIS TO DETERMINE AREAS OF RESPONSIBILITY FOR MACHINERY FAILURE

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ABSTRACT:
This paper illustrates how NOVA, its vendors and sub-vendors have successfully applied the "Team Concept" and "Fault Tree Analysis" to resolve problems encountered with seven (7) warranted turbo-compressor packages. It describes the "TEAM/FAULT TREE" process used, as well as the benefits of such an exercise (ie. the quick identification of a technical solution and the facilitation of commercial negotiations to a satisfactory conclusion for all parties concerned).

BACKGROUND:
In the fall of 1990 NOVA ordered three (3) fourteen (14) MW turbo-compressor packaged units from a General Packager, to be delivered in early 1992 to replace five (5) retired units at the Hussar Compressor station. During the design and manufacturing stage of this order an additional four (4) identical packages were added to the order to meet further system expansion requirements. NOVA had not previously dealt with this General Packager but had pre-qualified them prior to the order being placed. No previous relationships existed between the two companies so neither company knew what to expect of the other. This was the first time in many years NOVA chose to use a Turbine Manufacturer as the General Packager. Historically NOVA had always awarded packages to the compressor supplier as the prime. This General Packager, supplied their own power turbine and skid, but used subvendors to supply the gas generator, and gas booster. NOVA specified a magnetic bearing supplier they wanted used. The majority of these components existed elsewhere on other packages within the NOVA system.

Throughout the design and manufacture stages communications between the various subvendors were as could be expected for a first time order. NOVA and the General Packager incorporated a "Turbo-compressor
Administration Procedure" which resulted in numbered correspondence for both parties. All correspondence was channelled through a single contact in each company. The one window contact prevented mixed information from passing back and forth, prevented documentation from being lost or forgotten and simplified tracking and retrieving information.

All packages were delivered by the General Packager and the Compressor Supplier sub vendor and installed by NOVA with reasonable success. During the commissioning of the first two packages a serious failure occurred (92.07.14) which damaged and/or destroyed the:

- Magnetic Bearing radial rotors and stators
- Dry Gas Seals
- Impeller Eye Labyrinth
- Balance Piston seal

NOVA at the time attributed the failure solely to their own commissioning practices, which allowed the operation of the package close to the surge line for short periods of time. NOVA effected repairs, revised procedures and completed commissioning. Subsequently one and a half months later (92.08.30) a similar failure occurred while commissioning a third package. NOVA immediately intensified their own internal review of their commissioning procedures. As two similar failures had occurred very close together, NOVA began to suspect problems with the units as well. While the commissioning procedures were again under review a third failure occurred four days later (92.09.04) on a previously commissioned unit. This unit had been operating in a very safe area of the wheel map away from the surge line. As NOVA could not identify any further flaws in the commissioning procedures and this third package failed while under normal operating conditions, NOVA recognized this may not have been a NOVA procedural problem alone but could be combined with a package problem. At this point the customer vendor team was formed to research and correct any deficiencies present.

Subsequently, some months later (November) two additional serious failures were experienced, bringing the total to five failures in all. The latter failures were primarily axial damage and not radial as was seen earlier. These last two failures occurred while the units were running fully monitored after all known problems and concerns at that time had been addressed by the team. Fortunately, having the units fully monitored quickly pointed the team toward the final resolution of the problems.

TEAM BUILDING:

About the time these problems surfaced NOVA was undergoing a cultural change to incorporate teaming within the company infrastructure. NOVA could see the benefits of working as a team externally as well as internally.

An "effective team" means that the sum of each of the parts (individual contributions) is greater than the whole. There are three important factors in the cycle of a team, (1) building team, (2) using team and (3) sustaining team.

A team must recognize the expertise of all members and their contribution to the outcome. Each team member must be prepared to accept constructive criticism from his peers and be prepared to offer it as required. Team members must build trust, openness and honesty. It is alright to call yourself a team but if you are not working together your team will perform poorly and the benefits of working in the team will be negligible. A team needs something to focus on in order to provide work that can be truly shared and enable a "group" to evolve into "a team". Consensus is important and a consistent decision making process should be agreed upon.

To build the team NOVA and the other team members applied the following strategies, wherever and whenever possible:

- Demonstrate interest in the gathering and developing ideas of others through recognition
- Show respect for the feelings of others
- Encourage full participation of everyone concerned
- Specify intentions, direction, priorities to achieve clarity
- Establish/present clear, well thought-out objective
- Contact the right people
- Define how to work together
- Keep discussion focused on ideas rather than personalities
- Let all team members know they can question and disagree
- Indicate approval of free-ranging discussion
- Capture and restate important points during discussion
- Help others visualize links and relationships under consideration
DISCOVERY MEETING:
NOVA called a "Discovery Meeting" in Calgary as soon as possible after the third failure (92.09.09) with all affected vendors and sub vendors in attendance. NOVA’s immediate concern was in the compressor itself. NOVA’s contract was with the General Packager who supplied the entire drive train including the compressor which was manufactured by a sub vendor. It was mutually decided to involve the Original Equipment Manufacturers (OEM) at this stage, as time was of the essence and it was thought to not do so would be counterproductive.

Early in this contract NOVA perceived the General Packagers relationship with their Compressor Vendor was strained. This was perhaps because both companies had been in competition for this order. The team environment established, soon removed these roadblocks and the relationship grew positively between these vendors.

NOVA sought direct involvement not third party involvement from the General Packagers vendors, these vendors were the Compressor supplier and Magnetic Bearing supplier.

The Meeting Agenda

Introduction. A general overview of NOVA’s concern for the reduced power on the NOVA system due to the questionable reliability and down time of these recently purchased units which in turn was causing hardships for both NOVA and their customers. NOVA used this agenda item to communicate their need for an urgent solution to the issue at hand and request dedicated cooperation from the vendors. NOVA offered to lead a smaller team, not yet formed, to resolve the problem(s).

Review of Failures and Damage. NOVA carefully reviewed each of the three failures and histories of the other operating units to date, giving as many details as were known at that time.

Similarities. The meeting participants brain-stormed what, if any, similarities existed among the three failures. Operating conditions as well as package and station similarities were discussed.

Differences between 91/92. As NOVA had identical compressors purchased a year earlier, which had been operating successfully in their system, some time was taken in this meeting to determine what if anything was different with this compressor order.

Rotordynamics. The damage seen looked suspiciously like a rotodynamics problem, however, theoretical calculations did not show this to be a factor.

Identify the problem. A brainstorming session was held to determine any possible cause of the failures.

Long term Solution. As no obvious answer was available from the brainstorming session some thought was given to the time required to review all the possibilities before a solution could be recommended.

Interim Solution. A global speed restriction was introduced which returned the compressor units’ operation back to a speed at which similar compressor units were already operating, within the NOVA system.

Commitment. All parties restated their commitment to rectifying this problem as soon as possible.

Schedule. A follow-up conference call was booked for one week later.

Outstanding Action Items. A list of outstanding action items and issues was made and responsibilities assigned to the appropriate companies.

MEETING ANALYSIS:
Each individual in the room was there to defend their portion of the package and each was trying to steer the responsibility away from their portion of the package/company. Each team member of the Task Force had something to lose should the outcome of the study be unfavorable. Future business was at stake and their reputation among peers and associates. Without this concern the team would not likely have been focused as
quickly. Gradually the goal of the team shifted from being defensive to trying to solve the problem at hand.

During the discovery meeting the mood was far from "Team". It was evident from the onset that commercial issues tended to cloud the technical ones. Through consensus it was decided that the commercial issues would be put aside until technical success was evident. It was up to each company to sell this philosophy back to their companies’ contract/commercial departments and senior management. From this point on the task force team was considered the "Technical Task Force".

Honesty and trust were very important and practiced by all. As an example NOVA made a tremendous effort to be honest and above board with all aspects of the failures by exposing all operational/failure information which was captured in NOVA documentation. When NOVA exposed this information, others at first tried to use it to incriminate NOVA for poor operation practices. The challenge was to convince all parties that the problems were not solely operational but instead something deeper.

The meeting was attended by eighteen (18) NOVA individuals, five (5) of the General Packagers personnel, and eight (8) representatives of the various sub-vendors. Thirty-one (31) individuals from four (4) companies. This team was too large. All participants agreed that only one representative from each company should attend future meetings. NOVA offered to lead this team as they had the most to gain from a quick and efficient solution to the problem. Later the General Packager would lead the team through the testing and implementation stages of the repairs.

Roles and responsibilities were determined; future research and studies were agreed to with each responsible company; and agreements were made to hire third party consultants.

It was decided that whenever possible, conference calls would be used to keep people in touch rather than face to face meetings. Time would be better spent working on the problem than on travelling. Occasional face to face meetings were arranged as appropriate. Some consideration was given to Video conference calling however one vendor did not have ready access to such a system.

USING/SUSTAINING TEAM:
Many strategies used to build team were carried on through-out the "Using" stage by the team. The Team was intact for about eight months from the conception through: problem identification, analysis, design, shop testing and finally the implementation of the solutions. Additional factors used at this stage were to:

- Remain open to alternatives and new ideas by asking for initial suspension of judgement and by showing enthusiasm for interesting ideas.
- Offer creative suggestions and identify choices that others may consider.
- Review progress and restate purpose as necessary.
- Build a reputation for keeping the commitments you make.
- React objectively when your views are challenged by listening to peoples opinions unbiasedly.
- Present your views honestly in as much detail as appropriate, views must be supported with facts.

COMMERCIAL CONCERNS:
Each sub vendor agreed to provide the management, labor, parts and other required resources without prior agreement on cost responsibility. This was based on a mutual understanding by all four (4) parties that the commercial issues would be resolved after the cause(s) of the failures, and solutions, were determined and urgent repairs were carried out on an as-required basis to keep the pipeline operational.

Once the package design modifications were completed, the team shifted toward testing and implementation of these modifications in the field. After the design phase ended funds expended by each company grew quickly. This brought renewed commercial pressures to bear on the Technical Task Force. Up until that time (seven months) the Technical Task Force had been working extremely well as a team. The concern commercially was the perception by some that the amount of funds expended by each party was directly related to their degree of responsibility for the failures. These commercial pressures were resisted until two of the seven final retrofits were completed. At this point tensions were high and communication within the team became questionable.

NOVA felt commercial issues had to be dealt with and at least some progress made in that direction to be able to continue with the repairs. Who was to pay for the cost of the repairs? Previously, the company best suited to perform the work, paid for the work. Since the incident, many causes or proposed causes had been suggested (eighty-three
(83) base events on the fault tree) that could have contributed to or have caused one of the failures. Some factors were clearly the responsibility of one vendor or NOVA, others were not as clear. Because of this commercial pressure, the team’s trust and honesty, which had been working so well at the beginning of the task force, was clouded with personal and company biases.

It was in NOVA’s best interest to complete all retrofits quickly and to do this, rejuvenation of the team members’ integrity and commitment was needed. It was felt all parties would feel more at ease once the allocation of warranty responsibility was decided. The challenge to the team was to get a commercial team working as well as the technical team had.

NOVA proposed the use of a team based meeting for the commercial issues as it had worked so successfully with the technical team in the past. The Commercial team was made up of all the technical team members in conjunction with their companies’ commercial representatives. This team met for three days in Chicago (a half way point for most) where the responsibilities were determined for all parties.

In essence this was a "new" team and team building activities were once again important. As an example, prior to the meeting all team members were involved with drafting the agenda to ensure all agreed with the goals and objectives of the meeting.

The commercial team successfully used "Fault Tree Analysis" (FTA) which quickly reinforced the team concept throughout the meeting.

The technical participants built the fault tree and the commercial representatives provided the contract and commercial expertise required for the analysis.

FAULT TREE ANALYSIS

Normally Fault Trees are applied for the prediction of the risk and the reliability of a multi component system. What is the probability of an event happening in a multi-component or multifaceted environment? Fault Trees are not normally used after the fact as was the case here. Fault Tree Analysis was first originated by H.A. Watson of Bell Telephone Laboratories. Later Boeing further refined the process.

Fault Tree Analysis is the construction and analysis of a flow chart containing the interrelationship of many events which could lead to the cause of the "Undesired Event" in question. FTA is a way of logically looking at a complex system. It helps us find and focus on only those events believed to be significant to the occurrence of the "Undesired Event". Fault Tree has the ability to tie together a combination of errors or malfunctions in three (3) principal categories; human factors, equipment factors, and environmental factors.

1) Human factors: operational error, design error, maintenance error
2) Equipment factors: human errors, inherent equipment failures
3) Environmental factors: weather, third party systems, sabotage

This tool was EXTREMELY important in producing an environment where "teamwork" could be used to its fullest extent.

The immediate benefits realized by the team, using Fault Tree Analysis (FTA) were that the team remained focused, all sub-events were equally portrayed on the Fault Tree and no biases were pushed. Once a possible event was recorded, it was senseless to bring it up again as it was in clear view of everyone. The individual who brought up the idea would feel his idea had received equal treatment as it still remained on a "white board".

There is little, if any, back tracking and the individual who is obsessed with making sure he gets his point across feels sufficiently relaxed to concentrate on the others’ ideas. All team members felt they got their say in the solution/blame process and were therefore more apt to buy into the final result. FTA facilitated an excellent brainstorming session.

Only those ideas that could be proven to stand up to the scrutiny of the team members went onto the fault tree. All team members had more time to come to a consensus as to whether an idea was feasible. At the end of the exercise all team members agreed that any of the base (lowest level) events shown on the fault tree, either alone or in combination with other base events, could have been sufficient to cause the undesired event. All team members acquired a better understanding of each others points of view from the extensive discussions that were required to reach consensus on some of the contentious issues.
To construct a fault tree flow chart, start with the "Undesired Event" first. In NOVA's instance the "Undesired Event" was the "Compressor Damage/Shaft Flexed". Ask "How can this event occur?" What immediate sub-events or combination of sub-events had to be in place or present to have caused the "Undesired Event"? If none come to mind, redefine the "Undesired Event". Once this level is complete drop down another level, what sub-sub-events or combination of, cause a sub-event. Continue down the fault tree with these intermediate events until a base event is found to which responsibility can be clearly attached.

A FTA EXAMPLE
Figure 1 shows an over simplified Fault Tree depicting the assignment of responsibilities for a hypothetical "Coupling Failure" on a turbomachinery package with ten (10) base events. In comparison our actual fault tree had eighty-three (83) base events.

The Undesired Event "Coupling Failure" is followed by three sub-events; "Design Robustness", "Instigating Force" and "Unit Operating". These events are connected by an "AND" gate symbol which means all sub-events had to co-exist for the "Undesired Event" to occur.

Other sub-events are connected with an "OR" gate symbol which states that one or a combination of these sub-events had to be present for the higher event to take place. An example of this would be sub-sub-events "Imbalance" and "Misalignment" which could cause the higher sub-event "Instigating Force" alone, or in some combination.

Fault Tree methodology and symbolism can get quite
involved and tedious. It was our team's finding that by using very few basic symbols and logic, a satisfactory commercial and technical result could be achieved with minimal effort.

The majority of the logic used was either "OR" or "AND" gates. Occasionally "Inhibit" gates were used which simulate the effects of an amplifier/volume on the system. In this hypothetical example of "Coupling Failure," "Speed" was shown as an "Inhibit" gate between the "Instigating Force" and the "Coupling Failure" as it was thought the greater the speed the more severe the damage that could be realized.

Symbols used were either "Sub-Events" or "Base Events".

Suggested technical responsibilities and by implication commercial responsibilities are shown on this figure.

In NOVA's case, once all participants were satisfied that all the causes were accurately represented on the fault tree, the task shifted to analysis and the assigning of responsibilities of the failures.

Fault tree analysis assumes the probability of a base event(sub-sub.... sub-event) affecting the undesired event is higher if it is connected to the undesired event with more "or" and less "and" gates than another base event. As a result more responsibility could be shown, first for the number of the base events for which each company is responsible, and second in how those base events are connected. More "OR's" and less "AND's" should increase the probability of the base event being more relevant.

Our team did not require carrying the fault tree process to the probability analysis stage. As it turned out the brainstorming, discussion, and consensus facilitated through fault tree construction was more than adequate to come to an equitable and timely commercial settlement.

Without this "Fault Tree Analysis" tool it is hard to imagine that these parties could have reached an agreement without use of the court system. This would have hurt NOVA's relationship with their vendors and delayed resolution of the technical repairs.

CONCLUSION:

NOVA and its' sub-vendors successfully applied the "Team Concept" along with "Fault Tree Analysis" to provide the best technical and commercial solution to problems associated with equipment failures. NOVA achieved its goals and objectives in a timely and efficient manner and at the same time strengthened its relationships with its vendors.

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