ABB's Advanced Turbine Systems Program

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Abstract

U.S. Department of Energy, Office of Fossil Energy's Advanced Turbine Systems (ATS) program demands to develop the technologies required to increase the thermal efficiency of natural gas fired power plants to more than 60%, while maintaining NOx production at lowest levels, decreasing the energy costs to the consumers and without compromising the Reliability, Availability and Maintainability (RAM) performance of those engines.

ABB has been awarded with a technology development program in April 1995. The program objectives are to support DOE's ATS goals by addressing technical barrier issues in aero, cooling and material technology. These technologies will boost ABB's most efficient gas turbine, the GT24 with its advanced cycle system (GT24-ACS) above the specified program goals.

The efficiency objective requires to increase the turbine inlet temperature without increasing the cooling air consumption as a maximum of the compressor air is required to achieve the desired NOx levels in a premix combustor. Consequently the used turbine aero dynamic and cooling technology has to be improved. The use of thermal barrier coatings is a further mean to maintain material temperatures at elevated hot gas temperatures. By introducing this technologies reliability of this material systems becomes the key issue for success. Therefore ABB's program addresses TBC life time evaluation and degradation monitoring as well as kinetics of oxidation in steam of high temperature turbine materials.

The work is carried out in various ABB research and development facilities and at the Massachusetts Institute of Technology. Over the past 12 month substantial progress has been made by completing most of the material laboratory test work for TBC systems evaluation, by deriving correlations for advanced cooling schemes and by commissioning of a test rig to measure the interaction between main stream aerodynamics and surface cooling on stationary and rotating components under engine operation conditions.

The GT11N-series and the GT24 will be used as vehicles for engine demonstration of the technology developed under the contract. The first commercialization has been achieved with the introduction of the GT11NM retrofit turbine which boosts power output and efficiency of the GT11N engine significantly.

Program Objectives

ABB was awarded with a technology based Advanced Turbine Systems (ATS) contract in April 1995. The technologies developed under this program will allow to lift ABB's most advanced gas turbine the GT24 with its Advanced Cycle System (GT24-ACS) over the barriers specified by the Department of Energy. The goals are to exceed 60% efficiency in a gas fired power plant in an environmentally friendly way with NOx emission under 10 vppm (@15 % O2) and a reduction of consumer electricity costs by 10% without decreasing the Reliability, Availability and Maintainability (RAM) performance of toady's average gas turbine fleet.

The key program elements are:

- Advanced air cooled blading tests at ABB labs.
- Verification of Aero Thermal integration of a turbine stage at the MIT
- Steam cooling and sealing technology at ABB labs.
- Thermal Barrier Coatings at ABB labs.
- Technology demonstration

Key issue to DOE's aggressive targets are increase of firing temperature with a decrease of the cooling air consumption, as all air will be needed for the lean premix combustion process. This requires to optimize turbine cooling systems, introduce new materials, use of thermal barrier coatings and consideration of steam as cooling medium as outlined in Fig. 1.

To ensure that RAM performance goals will be met ABB conducts a detailed material test program at ABB Power Plant Laboratories (PPL) in Windsor, CT. PPL is ABB's center of excellence for evaluation of coating systems. [1]. The work for advanced cooling system is carried out at the Gas Turbine development lead center in Baden, Switzerland. For technology verification ABB cooperates with MIT's Gas Turbine Laboratories in Cambridge, MA. Engine demonstration will be carried out on customer's sites.

Advanced Air-Cooled Blading

The objectives of this task has been to extend the design data base for the most advanced cooling systems by addressing design uncertainties. Advanced impingement and convection cooling have been identified as areas to be investigated. Impingement cooling is quite often used for cooling of the inner and outer turbine annulus. With increased firing temperatures there is the need to increase the effectiveness of this cooling technology which is possible by combining impingement cooling with surface enhancement. A test matrix for test geometries has been set up and the design correlations for heat transfer and pressure loss have been derived. It could be shown that heat transfer can be increased significantly, especially for higher Reynold numbers. However the thermal conductivity of the metal plays an important role in the design of advanced impingement cooling schemes. The derived correlations have been used in the design of an upgrade of the ABBs GT11N turbine.

GT 11NM Gas Turbine - Engine Demonstration

ABB has a significant GT11D and GT11N gas turbine fleet operating in simple and combined cycle power plants. Many of this engines are approaching the end of their useful life. In order that the power producer may continue to operate a fleet with improved performance, ABB has utilized the Advanced Air Cooling technology partially developed under the ATS contract to uprate these engines with implementation of a completely new turbine module. This new turbine module is called GT11NM (Fig. 2). ABB used this uprating design to demonstrate the capability of advanced air cooling design as booster for efficiency and power output. The development goals included:

- increased power output at least 5%
- higher efficiency at least 3%
- maintain or improve RAM performance
- Reduce the cost of electricity

The GT11NM has been installed and tested earlier this year at Midland Cogeneration Venture which is a combined cycle power plant with 12 GT11N turbines coupled via HRSG to two steam turbines.

The test program included performance measurements, turbine vane row durability, various temperature and pressure measurements (Fig. 3). The tests revealed that the performance goals were exceeded significantly. The power output increase was measured to be 9.7% and the heat rate was decreased by more than 4% (Fig. 4) The temperature measurements showed that the material temperatures are lower as before the upgrade which leads to the conclusion that the already outstanding RAM performance history of the engines will be maintained.

Advanced Steam Cooled Vanes

ABB investigates under this task basic technologies for the design of steam cooled components. The favorable heat transfer properties of steam admit the possibility of closed loop fully internally cooled turbine components even under ATS firing temperatures. The favorable heat transfer to flow resistance ratios should permit enhancement of cooling passages internal heat transfer effectiveness. However steam as coolant medium involves new challenges for sealing, structural / material component design due to the considerable higher pressure difference between the cooling passages and the main gas flow, that acts as a mechanical load on the wall. The fact that steam is generally not available during the startup of the engine means a switch over from air to steam cooling will be required.

Basic lab experiments to generate a heat transfer, pressure loss data base have been conducted for a wide variety of wall model geometries. This data are used for prototype nozzle design for the GT11N Turbine. Engine demonstration of the technology is planned for next year.

Turbine Aerodynamics and Aero Thermal Integration

Turbine performance improvement for high-efficient cooled stages requires a detailed understanding of the interaction between the main stream aerodynamics and the discharged cooling air flow. The interaction of all effects can only be

measured under exact engine conditions. However this involves some difficulties and quite often the size and energy costs are not justified for those measurements.
ABB choose the approach to use the unique test facility at the Massachusetts Institute of Technology's Gas Turbine Laboratory, that has the capability to measure accurate steady state and time resolved turbine performance and surface heat transfer under engine conditions using a blow down wind tunnel. A detailed description of the blow down test facility is given in [2]. Blow down tests offer high test flexibility at low hardware and energy costs. The existing blow down tunnel (Fig. 5) was modified for the scaled ABB turbine stage. The stage scaling is summarized in Table 1.

	Engine	Test Rig
Geometric Scale Factor	1.00	0.25
Ratio of specific heats	1.28	1.28
working fluid	Air	Argon - CO2
Pressure ratio	2.0	2.0
Wall temperature to Gas temperature ratio	0.65	0.65
Corrected speed	100 %	100 %
Mechanical speed	3600 RPM	6000 RPM
Reynolds Number	100 %	66 %
Run Time	Continuos	0.3 s

Table 1.

As the time window for the measurement is small (0.3 s) and the required measurement accuracy is very high a great effort has to be spent in developing and calibration of the measurement probes. [3]. The following quantities are recorded during a test run: turbine stage performance, calculated from total temperature and total pressure ratios and directly measured over the shaft torque, main stream and cooling mass flows, end wall static pressures, radial and circumferential distribution of total temperature, total pressure and flow angles after the nozzle and after the blade, surface heat transfer on the airfoils and end walls.
The blow down tests for the uncooled stage have begun and the tests with cooled stage are scheduled for early 1998.

Material Program

Evaluation of TBC Systems in High Thermal Gradients

The design of reliable TBC - Systems requires to have detailed knowledge of the failure mechanism of the system. Oxidation and thermal gradients are the dominant root causes for an early degradation of a TBC system. Within ABB's high temperature material test program different TBC systems are investigated using a natural gas fired burner test rig (Fig. 6) to generate a rapid oxidation. The test rig allows internal air cooling of the test bars (Fig. 7) to simulate a temperature gradient. 8 probes were simultaneously exposed to the gas flame to achieve a material temperature of 1100 degree C with a rapid cool down to 150 degree C every hour as a temperature cycle. The probes were metallographically assessed (SEM). Engine component samples were taken as a benchmark to prove that the chosen test conditions are capable to evaluate a TBC system. Fig 8 shows the similarity of the build up oxide structure of the engine component and the test bar using the same TBC system.

Monitoring the Degradation of TBC Systems

Currently there are no reliable NDE methods for condition monitoring of TBC systems available. Standard practice until now is cut-ups and metallographic assessment. Eddy current or ultra sonic signals can be used as NDE to determine the amount of oxidation of the bond coat. Under this task different TBC systems are oxidized to predefined conditions. NDE methods are calibrated using metallographic assessments of the same bars. Fig. 9 shows the obtained US signal for different amount of bond coat oxidation. Additionally cross reference is made to components from TBC engine tests.

Thermo Mechanical Fatigue of TBC Systems

Since components coated with TBC are subject to severe mechanical and thermal loads which vary during engine operation the response of thermal barrier coated components to TMF is an important aspect of design. TMF testing is carried out on different TBC systems using a CMSX4 single crystal substrate material. The test conditions are a 50 to 1000 degree C ‘out of phase” strain controlled TMF cycle. The current results indicate that the TBC systems decreases the cyclic life time of a component. Fig. 10 shows a typical fracture surface of the test bars.

Kinetics of Oxidation in Steam

The use of steam as a coolant poses the risk of introducing new failure mechanisms into a component design. Besides increased mechanical loads the long term oxidation behavior of super alloys in a steam atmosphere has to be known. Previous work at ABB’s laboratories involved short term exposure of a wide range of alloys to a steam atmosphere. The current work is directed to long term exposure of commercially available super alloys, i.e. IN738, CM247, a typical DS alloy and CMSX4 a typical single crystal alloy.

The test bars are exposed in a test bed (Fig. 11) to a steam atmosphere at elevated temperatures and atmospheric pressure. The test bars are periodically removed for evaluation. The oxide growth is measure by weight gain and metallographic assessment. The obtained results indicate that the oxide growth rate is higher than in an air atmosphere. The higher Cr content materials start spalling off bigger scaled oxides in less than 1000 h resulting in a weight loss (Fig. 12). The low Cr alloy CMSX4 is gaining weight for more than 5000 h under the same test conditions.

Conclusion

ABB demonstrated that the advanced air cooling technology is able to contribute to a significant increase of power output and power plant efficiency. The applied design methodology and the step by step introduction of laboratory and engine proven technology allows to minimize risks and to maintain RAM performance which is an important success factor in the current competitive market environment.

A further mile stone was achieved by commissioning a turbine test rig to measure aerodynamic and cooling interaction under engine conditions. It is

expected that the test results will enable the design engineers to increase the performance of next turbine design and simultaneously decrease the cooling air consumption.
The detailed test program for TBC systems will ensure that introduction of TBC as a basic design element in a high temperature gas turbine does not compromise the RAM performance expectations.
The design challenges for introduction of steam as a coolant medium are addressed and basic experiments to over come the difficulties are carried out. A prototype demonstration design is ongoing.

Acknowledgment

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[3] Guenette G.R., Epstein A.H., Giles M.B., Haimes R., Norton R.J.G.: Fully scaled Transonic Turbine Rotor Heat Transfer Measurements, ASME 88-GT-171, 1988

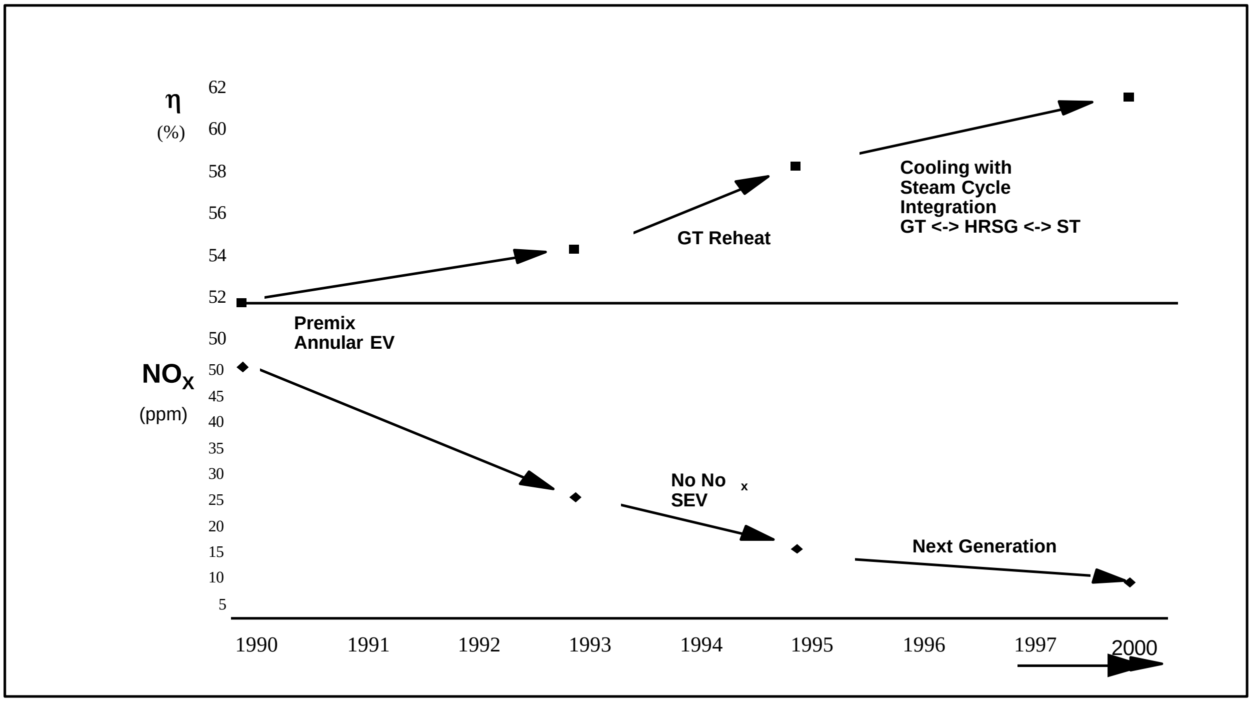

Fig. 1 Development Steps

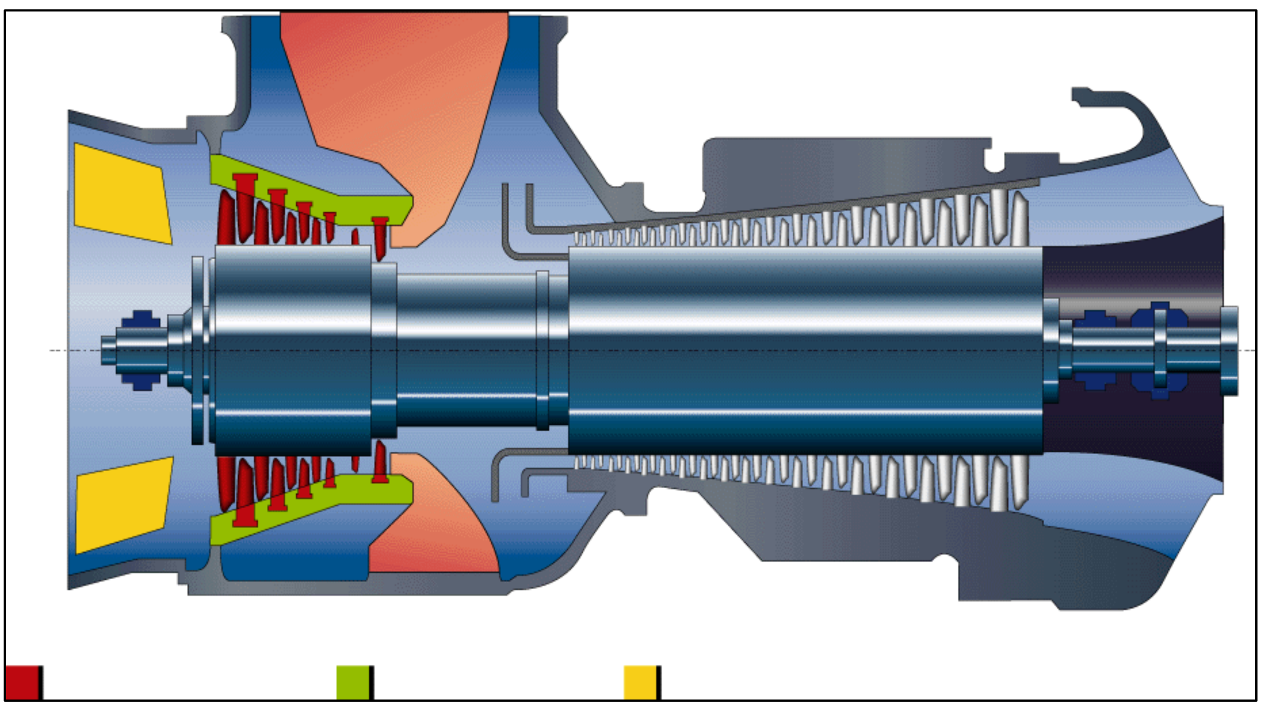

Fig. 2 GT11N with GT11NM Turbine

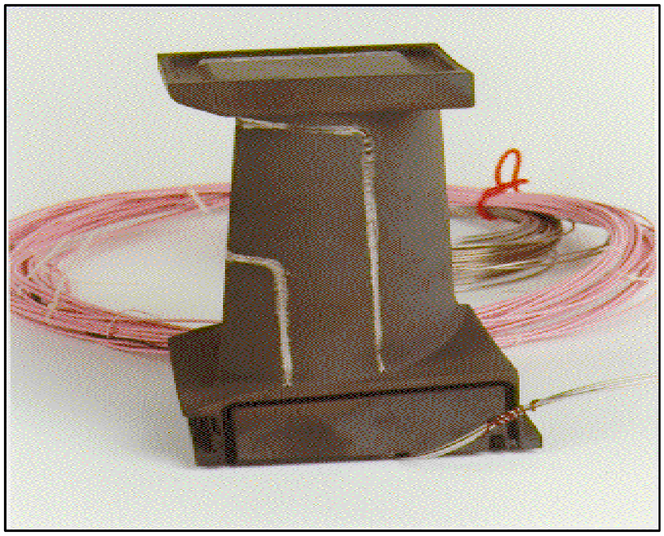

Fig. 3 Vane Instrumentation

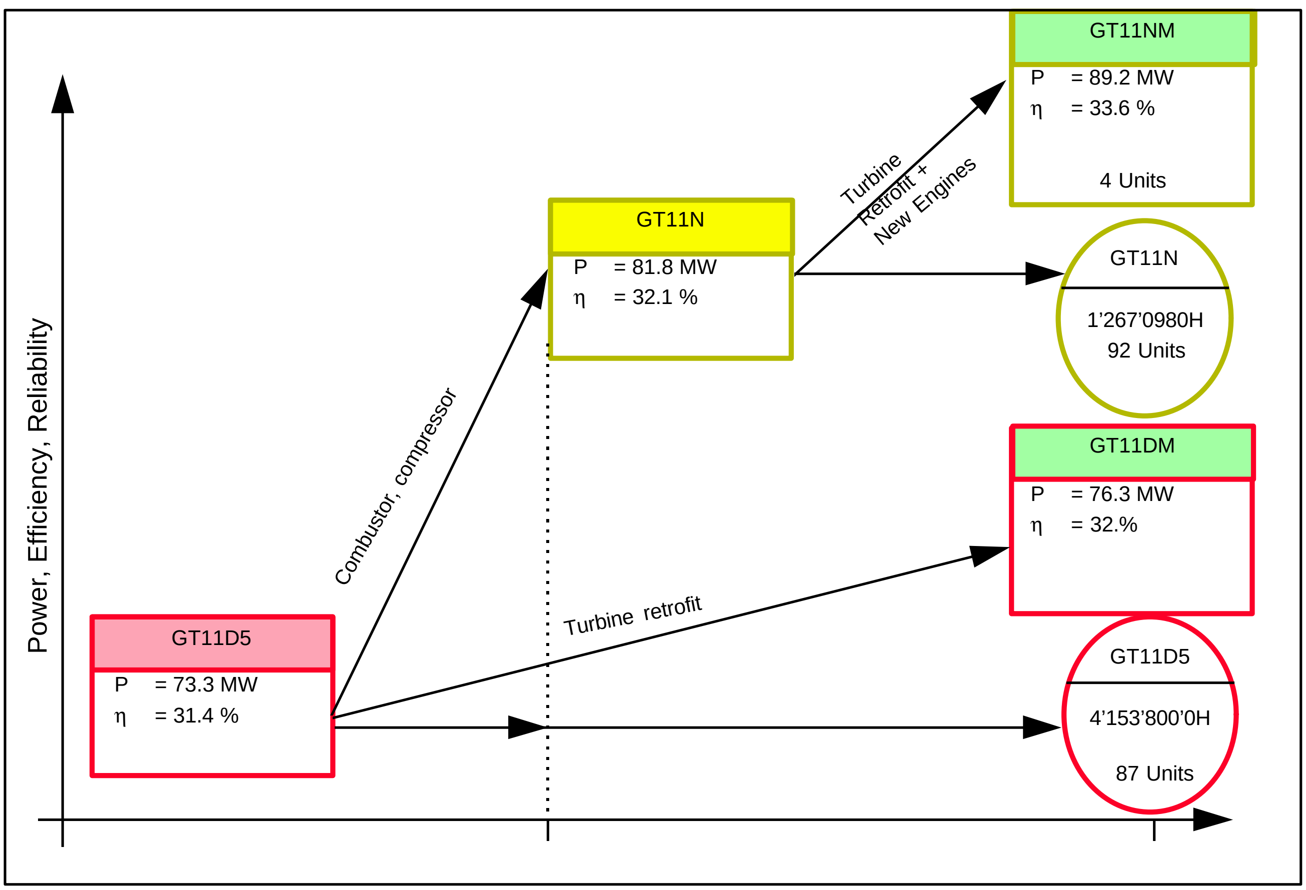

Fig. 4 Performance improvement Turbine upgrade

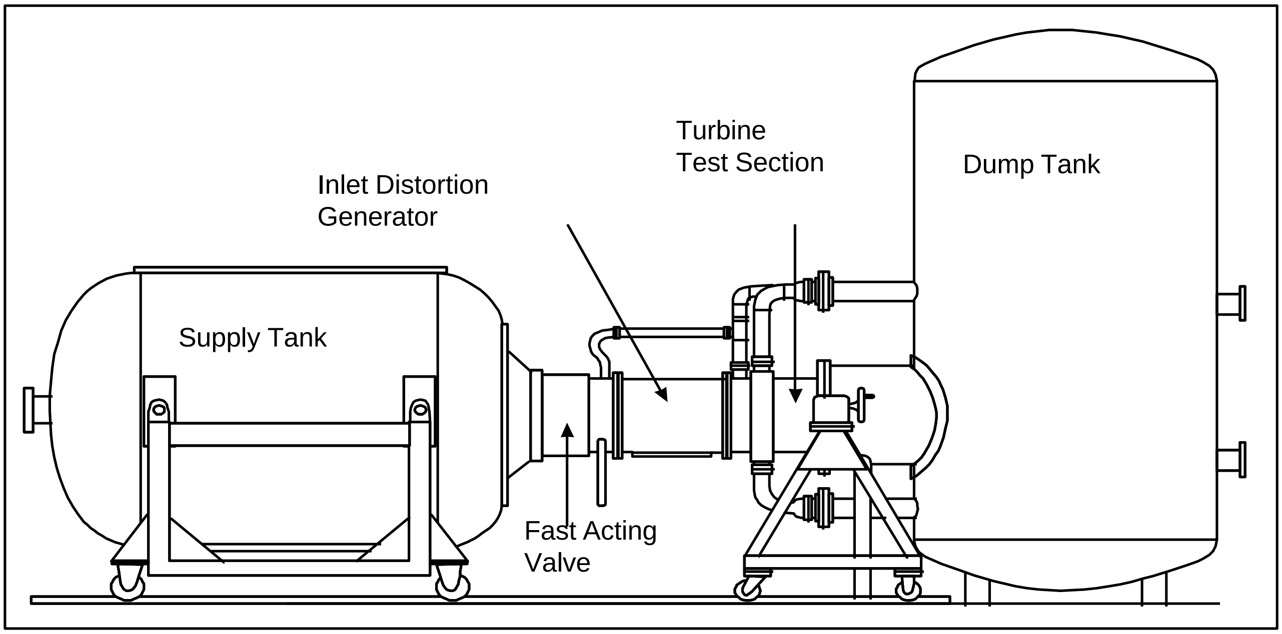

Fig. 5 MIT Turbine Test rig Blow Down Tunnel

Fig. 6 Burner Test Rig

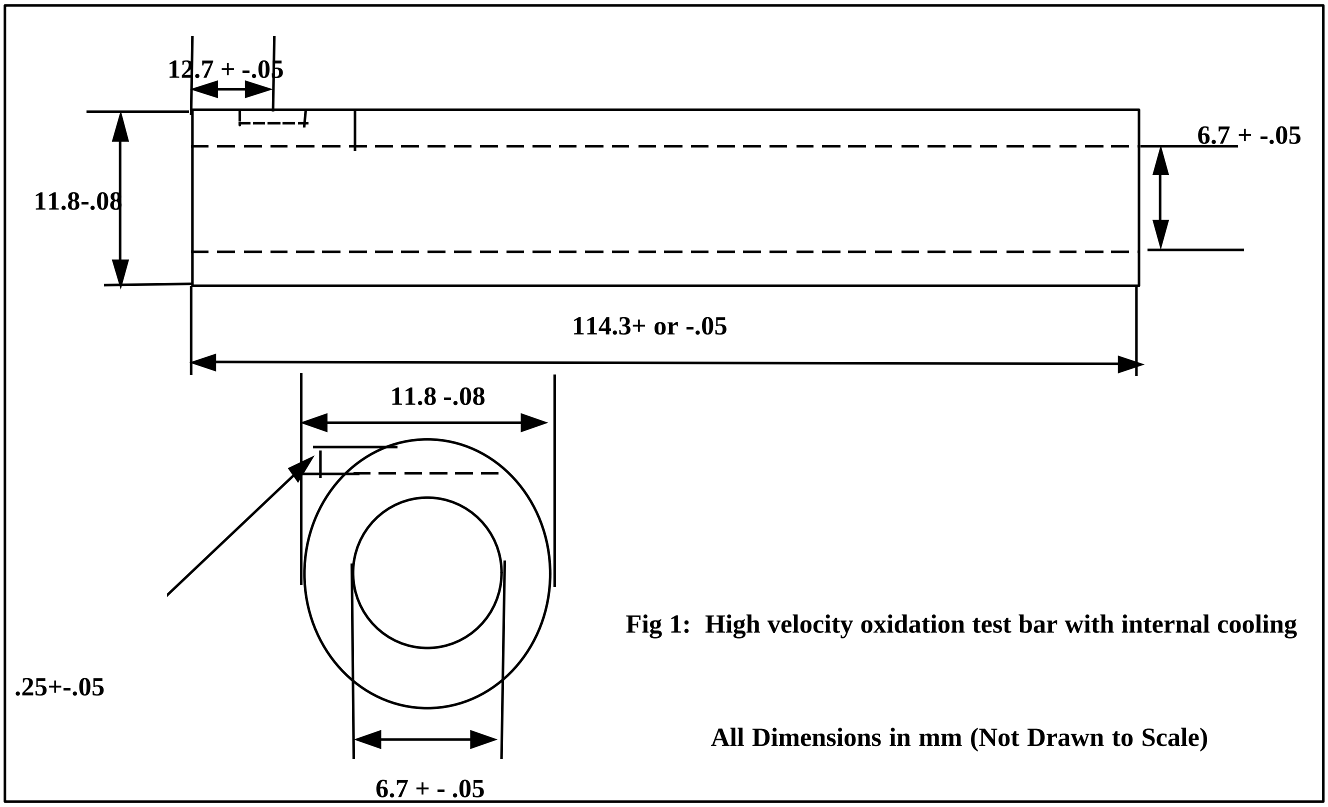

Fig. 7 Test bar Geomatry

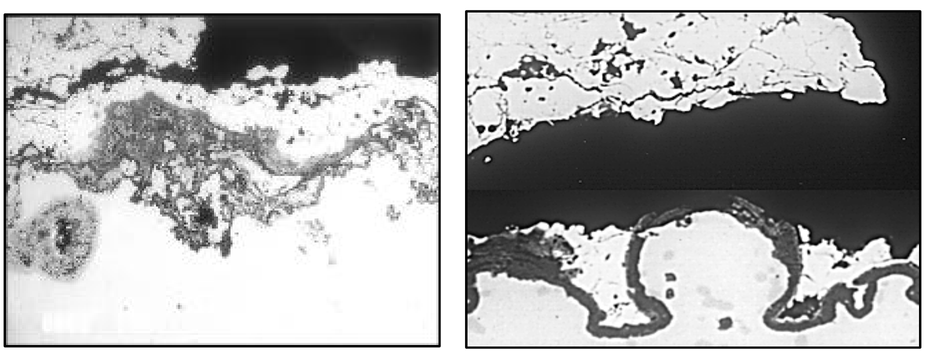

Fig. 8 Oxide structure in Buner test Rig (left) and in engine (right)

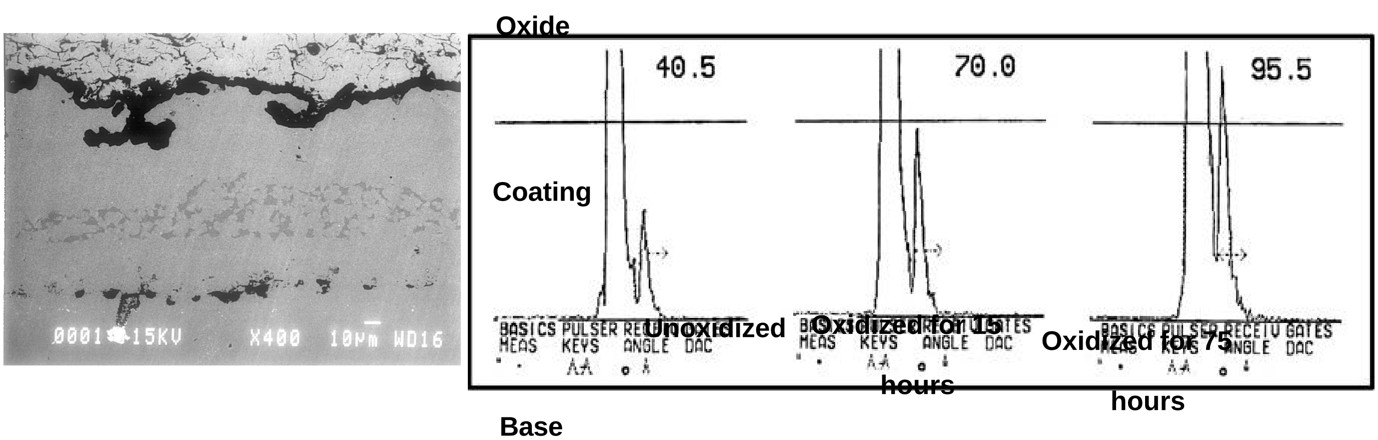

Fig. 9 US signals Bond coat degradation

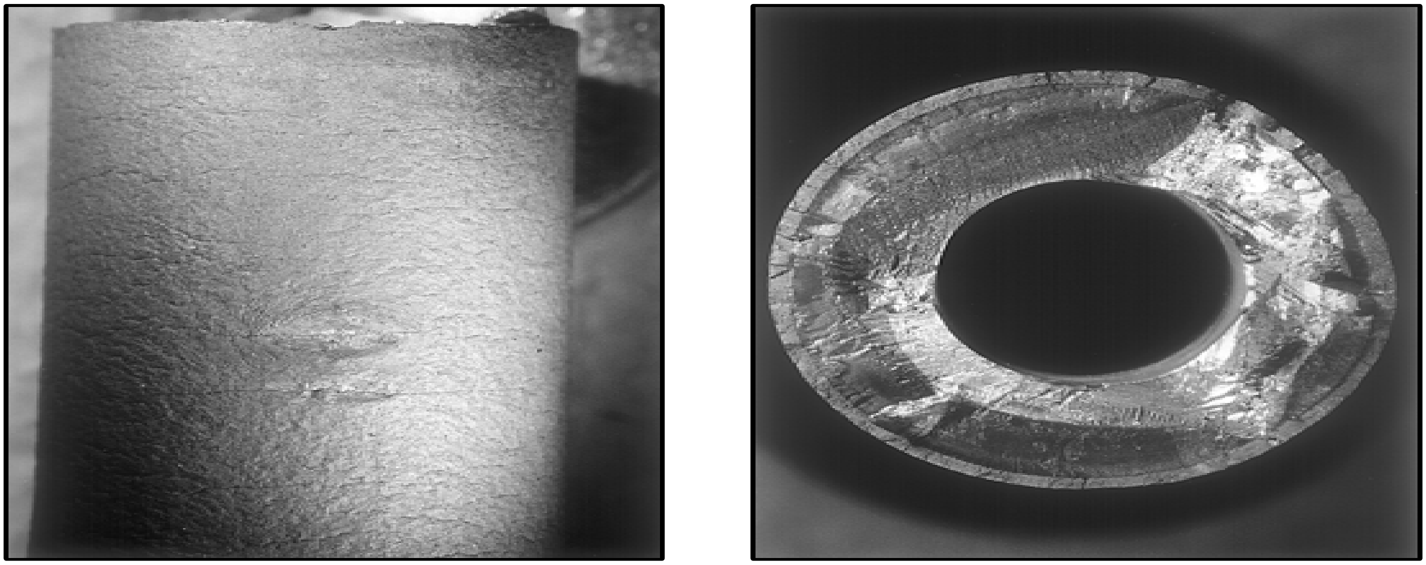

Fig. 10 Fracture surface TMF testing

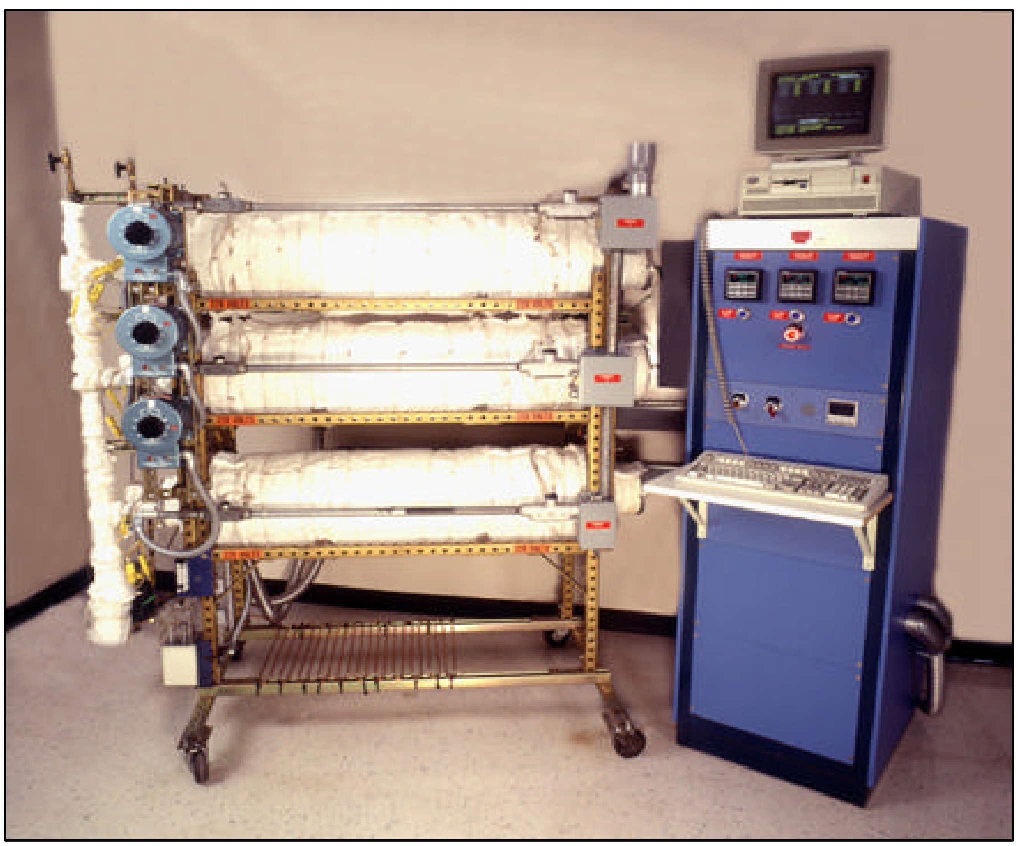

Fig. 11 Steam Oxidation Furnace

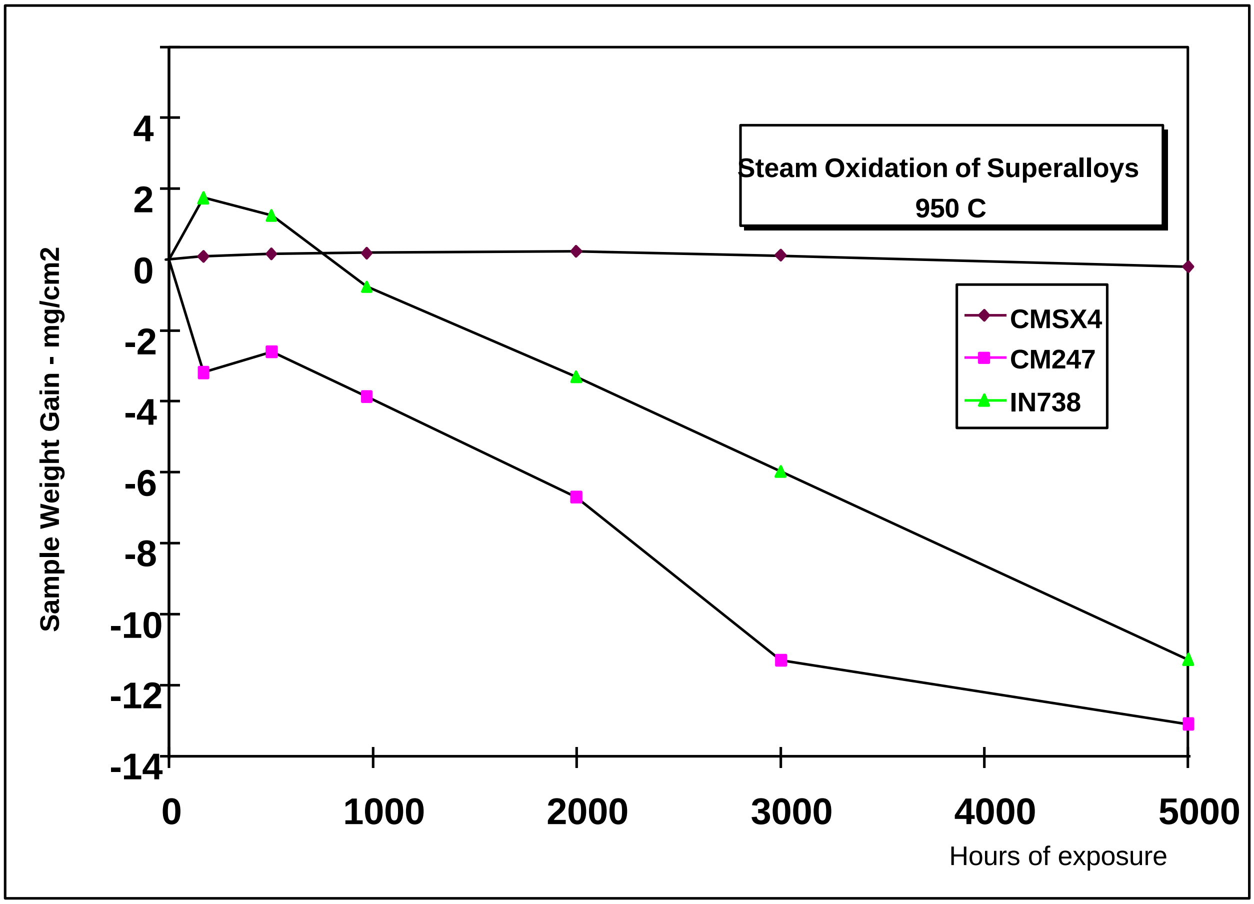

Fig. 12 Oxidation rate of super alloys in steam atmosphere