LIFING METHODS FOR COMPONENTS

OPERATING UNDER CREEP-PLASTIC LOADING CONDITIONS

CPLIFE

SYNTHESIS REPORT

FOR PUBLICATION

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	Rolls-Royce Ltd. & Co. KG (RRD)
	Consiglio Nazionale delle Ricerche - Istituto per la Tecnologia dei Materiali e dei Processi Energetici (CNR)
	QinetiQ (QQ)
	European Commission Joint Research Centre - Institute for Energy (JRC)
	Fiat Avio SpA (FIAT)
	Motoren-und-Turbinen-Union München GmbH (MTU)
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CPLIFE SYNTHESIS REPORT

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1. SUMMARY

1.1 Keywords

Combustors, creep-fatigue, thermomechanical fatigue, lifing, rig testing

1.2 Abstract

The aim of this 52-month RTD programme, which focused principally on combustors, was to produce verified lifing methodology for the design and in-service support of all gas turbine components that are subjected to both creep and plasticity during every engine cycle. At its core was the development of three types of materials behaviour model and their implementation in the Finite Element (FE) programs used for component design:

- Deformation models to predict stabilised component stresses as efficiently as possible
- Crack initiation/damage models, based on parameters from the FE calculations, to predict component lives at the design stage
- Crack growth models to allow safe inspection intervals to be specified where in-service problems exist

Development of the models was based on thermomechanical fatigue (TMF) and isothermal test results on standard laboratory specimens and specimens containing representative component features. Their final verification used results from rig testing on sub-elements of combustor and turbine casing geometry under component loading conditions. Two materials were studied, C263 and Haynes 230.

An overall matrix of 508 specimen tests was performed, 310 on C263 and 198 on H230. High quality data were produced for the two materials that allowed clear behavioural trends to be identified and represented in the materials modelling work. The large number of different test types and specimen designs allowed materials understanding to be built up step by step and transitioned from plain specimens through to components. This was facilitated by the development of novel techniques for TMF testing of featured specimens.

The deformation modelling activity produced a number of complementary approaches that could predict stabilised component stresses and strains to the required accuracy. Very good lifing correlations were obtained for isothermal specimens tested under a wide range of loading conditions, although extension of the models to TMF cycles and laser drilled holes proved difficult. The crack propagation modelling work proved successful in predicting the behaviour of plain and featured isothermal specimens.

Methods for reducing the run times of non-linear finite element analyses were investigated, but in general the resulting loss in accuracy was unacceptably high. This remains an important area for future research in order to implement the improved lifing methods from this programme without increasing development timescales for new components.

Three rig test types were developed to allow the accuracy of the life prediction methods to be assessed on engine hardware run under controlled conditions, combustor tests on a single component and two in series plus a scaled turbine exhaust casing. A series of technical problems with both combustor tests, however, prevented the components being run to failure and providing datum points for verifying the lifing models. Both these facilities, however, remain an essential part of their companies' strategies for introducing new combustor designs. The turbine exhaust casing rig achieved all of its aims and was able to crack the component being tested in the expected location. Life predictions for this component agreed very closely with the test result.

The thermal and structural analysis work on the rig tests allowed new techniques to be developed for reading thermal paint data onto an FE mesh and analysing sub-models of local regions of the component. These will help to reduce analysis times for new components.

Overall, significant progress was made on developing and verifying lifing methods for combustors and turbine casings. The lifing curves derived for holes in combustors, however, are currently considered to be over-conservative. Further work is planned using the CPLIFE results to allow design lives based on these data to be increased.

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2.2 Consortium Description

Rolls-Royce

Rolls-Royce plc is a global company meeting present and future requirements of civil aerospace, defence and energy markets, with facilities in 14 countries. Its core gas turbine technology has created one of the broadest ranges of aero engines in the world, with 55,000 engines in service with 300 airlines, 2,400 corporate and utility operators and more than 100 armed forces, powering both fixed and rotary wing aircraft. In addition, more than 30 navies use Rolls-Royce propulsion. Energy markets include the oil and gas industry and power generation.

Rolls-Royce pioneered gas turbine technology for aerospace, power generation and marine propulsion and is involved in major future programmes in these fields. These include the Trent aero and industrial engines, the Eurofighter Typhoon and Joint Strike Fighter combat engines, the WR21 marine engine and leading edge water jet propulsion systems.

Rolls-Royce's main contributions consisted of project co-ordination, materials modelling and the design and running of a cyclic fatigue test using a twin combustor rig.

Alstom Power Sweden

Alstom Power Sweden (formerly ABB Stal) designs and delivers plant for power and heat production. APS has been in the business for over a century, with roots in the pioneering inventions by Gustaf de Laval and the Ljungström brothers. APS regards an improved level of competence in constitutive modelling and lifing as fundamental for future business. The cost and effort involved, however, mean that the only suitable way of developing the required methods is via a collaborative approach.

APS focused on modelling and constitutive testing in the project, with particular emphasis on extrapolating material behaviour out to the long cycle times experienced by industrial gas turbine components.

FIAT AVIO

FIAT AVIO S.p.A. is the Aerospace Company of the Fiat group. It has been operating in the aeronautic business since the beginning of the century. Recently Alfa Romeo Avio has been incorporated.
Besides activities in power generation and space, Fiat Avio designs, develops and produces:

- aero engine components for commercial and military aircraft
- engine components and power transmission for helicopters
- turbines for marine propulsion

Fiat AVIO's core business includes providing spares and technical assistance for product support.

Fiat AVIO's contribution to CPLIFE was the model verification activity by performing detailed transient thermal and structural FE analyses of the TURBOMECA rig tests.

Rolls-Royce Deutschland

RRD was established in 1990 as a joint venture of BMW AG and Rolls-Royce plc. The core business activity of RRD is the development, manufacture and maintenance of aero-engine propulsion systems for civil aircraft applications below 23,000 lbf.

The objectives of this project are within the strategy of RRD to design reliable and environmentally friendly low weight and high performance aero engines. Within the project, RRD contributed know-how of aero engine technology and definitions for the combustor application from an end user's perspective. Results from this programme will help RRD to enhance its competitive position in the market place and to respond to the challenge of competing with the US aerospace industry.

The particular contributions within the interlinked tasks of the project were unified constitutive modelling, parameter identification and software implementation, crack initiation modelling using strain energy density concepts and the structural analysis and lifing of a partner's rig test.

CNR-TeMPE

CNR-TeMPE (Consiglio Nazionale delle Ricerche - Instituto per la Tecnologia dei Materiali e dei Processi Energetici) has extensive experience in lifetime investigation methods involving creep, low cycle and thermomechanical fatigue and crack propagation testing. These methods are supported by microstructural studies using optical and electron microscopy, fractography and microanalysis. Materials applied in power plant structures, aero and land based advanced gas turbines are the main subject of the research. The institute has often acted for the aero engine industry in a consultancy role, and has been involved since 1973 in EU concerted actions COST 50 and 501. The institute has also participating in other BRITE-EuRam programmes. Considerable expertise has been gained in examination of the mechanical properties and microstructure of a wide range of gas turbine materials such as sheet material for combustors, wrought disc alloys, conventionally cast and directionally solidified alloys for blades and vanes, creep resistant titanium alloys and dispersion strengthened alloys. CNR-TeMPE's activity in the programme focused on high temperature materials testing and mechanism informed creep modelling.

QinetiQ

QinetiQ (formerly the Defence Evaluation and Research Agency – DERA) is the largest organisation in Western Europe devoted entirely to research and development. One of its current major objectives is to facilitate the transfer of its technologies, developed primarily for military use, into civil market sectors and hence contribute to wealth creation. The concept of partnership is key to QinetiQ's business culture and previously as DERA it had been engaged in collaborative ventures with industry for many years, including within European programmes.

The work was carried out in the Structural Materials Centre (SMC) sector, which was the first of DERA's Dual-Use Technology Centres. It aims to bring together civil and defence related research workers and to provide an environment in which the cross-fertilisation of ideas and technologies can occur. The role of QinetiQ within the project was to develop non-linear crack initiation and growth models that can be applied to the in-service support of gas turbine components and perform specimen testing, including TMF, for the different modelling activities. In this respect, it drew on its extensive experience in lifing problems, in which capacity it has established itself as a major European authority.

EC-JRC-IE

The Institute for Energy (IE) is a part of the Joint Research Centre (JRC) of the European Commission. JRC-IE provides scientific and technical support for the conception, development, implementation and monitoring of community policies related to energy. Special emphasis is given to the security of energy supply and sustainable and safe energy production.

The Institute for Energy supports EU actions by executing its specific research programme in the areas of clean and sustainable energy, nuclear reactor safety and medical applications of nuclear technologies. The sector of IE participating in the proposed project focuses its research on evaluating the mechanical behaviour of advanced materials, optimisation of material properties, reliability issues, the modelling of materials performance, the joining of dissimilar materials and on pre-normative research and standardisation, addressing metallic alloys, monolithic ceramics and ceramic matrix composites. In the field of metallic alloys a wide experience concerning nickel based superalloys for aero gas turbine applications exists which has been accumulated through contract research projects with, amongst others, the aerospace industry.

EC-JRC-IE's contribution to the project was in the co-ordination of the specimen testing programme and TMF testing and methods development, drawing on the group's unique test facilities and its scientific project management skills.

MTU

MTU is the most experienced German aero engine company. It was originally engaged in the production of military engines, but its involvement in the civil market has increased continually and now accounts for 80% of sales. MTU collaborates with different aero engine manufacturers, mostly as a smaller partner, but participates in engines such as the GE JT8D, the IAE V2500 and the PW4090/98 engines for large civil aircraft. It co-operates with Rolls-Royce in the Eurojet EJ200 for the Eurofighter Typhoon and with other European partners in the MTR390 engine for the Tiger helicopter.

MTU continuously works to improve the efficiency and life of engines, not only to reduce the operating costs but also pollution.

Within CPLIFE, MTU developed methods for predicting the life of spoked structures such as turbine exhaust ducts. These were verified by performing a cyclic rig test on a scaled down component with applied thermal and mechanical loads.

SENER

SENER is a private group of engineering companies created in 1956. Its objective is the application of innovation and technical development to engineering services. Its fields of activity are the following: space, aeronautics, communications, electronics, power generation, industrial plants, civil engineering, process plants and marine systems.

SENER is participating in the European Fighter Aircraft (EFA) programme with RR, MTU, FIAT Avio and ITP. The EJ200 engine modules designed by SENER have reached the high requirements of the programme with respect to their performance, mass, maintainability, reliability and life.

SENER is also collaborating with ITP/RR/RRD in the design and analysis of components for RRD engines and has participated in previous BRITE-EuRam projects such as BE6021. Within this project SENER developed life prediction methods for use in the design of new components.

TURBOMECA

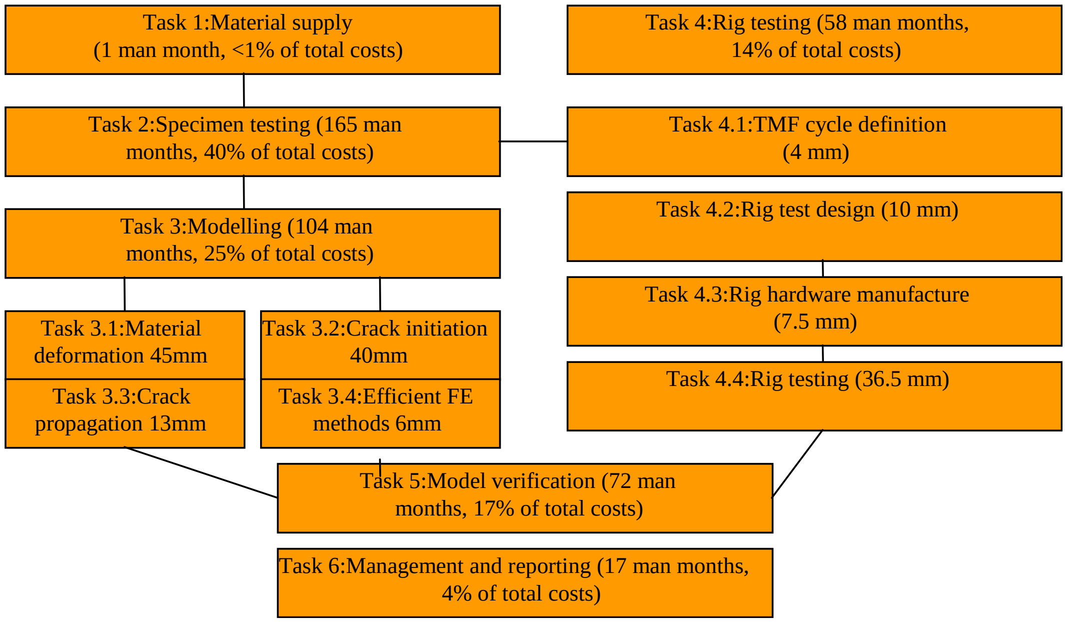
TURBOMECA is one of the major European gas turbine manufacturers with more than 60 years experience. Its aim is to maintain and improve its European leader position in the design and manufacturing of small and medium gas turbine engines for helicopters, turbojets, turbofans and auxiliary power units.

The expansion of its world market share, especially in North America against competition from the US manufacturers is a core part of its strategy. The technical aims are to improve engine efficiency and performance, including specific fuel consumption and power to weight ratios, to remain competitive and reduce development costs. Such objectives cannot be achieved without effective European co-operation to share the ever increasing research and development costs.

TURBOMECA's main contribution to the project has been the design and test of small-scale combustors containing different cooling features.

3. TECHNICAL ACHIEVEMENTS

The programme consisted of six tasks as shown below:



CPLIFE Project Structure

Figure 1

The specimen testing of Task 2 provided input data for the main project activity, the materials behaviour modelling of Task 3. Standard test types were performed in order to determine parameters for the deformation, crack initiation and crack propagation models. The validity of these models was then established by using them to predict the behaviour of more complex tests such as fatigue under non-isothermal conditions and on specimens containing laser drilled holes. The most complex loading conditions that can be reproduced in the laboratory still fall short, however, of those experienced by components such as combustors and turbine casings in service. For this reason, final verification of the models depended on being able to predict the fatigue lives of real components tested under representative loads. Task 4 developed the corresponding novel component testing techniques for combustors and casings. Interpretation of both the complex specimen and component tests required detailed finite element analysis work, the subject of Task 5.

The principal deliverables from each of the technical tasks are described in the following sections.

<u>Task 2: Specimen Testing</u>

Task 2 was divided into two parts, the development of advanced specimen testing methods and the generation of test data for model development and verification.

Task 2.1: Test methods development

There were two main activities in Task 2.1, both associated with thermomechanical fatigue (TMF) testing.

The JRC work on TMF contained two novel aspects, testing in vacuum and using specimens containing cooling holes of similar geometries to those used in combustors. Testing in vacuum meant the forced air cooling (by means of jets of cold air blown onto the sample surface) conventionally used by JRC could no longer be used. Consequently, cooling of the sample ends was the only method to enhance the specimen cooling rate and minimise the cycle time. To this end, cooled clamps were placed around the shaft of the samples to maximise heat transfer. Cryogenic cooling was attempted, but was found to be ineffective. Optimum specimen heating and cooling rates were determined for the vacuum tests.

Appropriate designs for test pieces with angled and perpendicular holes were produced by JRC in conjunction with QQ and RR, aiming to keep the cross-sectional area similar to that of the isothermal strain controlled fatigue specimens tested in the programme. A rectangular gauge section of dimensions 14.3 x 3mm was selected, with the angled hole at 20° to the specimen surface. The hole diameter was 0.7 mm, consistent with the dimensions of typical combustor effusion cooling holes. Finite element stress calculations on this geometry showed the stress concentration at the 'acute' edges of the hole to be 7.5. The 90° hole design had an elastic stress concentration of approximately 2.8.

The use of induction heating for this specimen presented a significant technical challenge because the corners of specimens are heated more rapidly than regions further away from the extremities. Normally this is not a significant problem, as a small temperature gradient from edge to centre of sample can be tolerated. However, when features such as holes are included, the tendency is for the rims to heat up more strongly than the surrounding material. As the holes in these samples are representative of those used for component cooling, they should ideally be at a lower temperature than the surrounding material. This can be achieved by heating the region around the hole mainly or entirely by conduction from surrounding material. By optimising the coils which were used, the direct-through holes showed no effect on the temperature profile, and the angled holes showed a slight (~5°C) temperature rise. This was judged to be acceptable.

For its industrial gas turbines, APS has a requirement to understand long term material ageing effects under loading conditions representative of combustor hot spot and cold spot features. This requires a facility that can generate component-like multiaxial stress fields and can be run for long periods of time at reasonable expense. A variety of different rig concepts were considered, including infra-red heating of the centre of a plate and mounting heaters inside a cylindrical test specimen.

The most practical design, however, consisted of a circular plate specimen in H230 heated by burnt fuel from an array of cylindrical tubes. The heat flux was concentrated in the centre of the plate, and cooling air was directed in a ring around this region to generate temperature gradients and hence thermal stresses. Figure 2 shows the rig in operation. By changing the arrangement of the heating tubes and cooling air a cold spot feature could also be tested.

ALSTOM long term TMF rig being run in hot spot configuration Figure 2

During running, however, it became clear that the high heat fluxes were heating the chamber used to mix fuel and air to the point where there was a risk of explosion. Although design modifications were considered, the cost and associated timescales ruled out further development work within CPLIFE.

Task 2.2: Specimen Testing

A total of 508 specimen tests were performed, 310 on C263 material and 198 on Haynes 230. Seven temperatures, ranging from 20 to 950°C, were used for the specimen testing with detailed studies of the fatigue behaviour of both materials performed at 300, 600, 800 and 950°C. The reasons for selection of these temperatures are listed below:

20°C: Engine component minimum temperature

300°C: TMF cycle minimum temperature, chosen to have similar properties to 20°C

600°C: Onset of creep, representative temperature for combustor heads and meter panels

700°C: Increasing creep influence but inelastic behaviour still dominated by plasticity

800°C: Creep-fatigue behaviour, maximum temperature for in-phase combustor areas

900°C: Reduced influence of γ' strengthening mechanism in C263 material

950°C: Creep dominated behaviour, maximum combustor wall temperature

The temperatures and the associated cycle waveforms were based on the results of the component Finite Element (FE) analyses carried out in the first year of the project in Task 4.1.

The test types were divided into three categories. 264 'baseline' tests (tensile, creep, plain specimen Low Cycle Fatigue (LCF), crack propagation etc.) were performed to determine parameters for the materials behaviour models. 139 'sensitivity' tests (plain specimen TMF, multiaxial LCF, vacuum LCF) were then used to define how to extend these models to geometries and loading conditions more representative of engine components. Results from the final series of 105 complex 'verification' tests (featured specimen TMF and LCF) were then compared with predictions from the models.

Tensile tests on both materials were performed by FIAT at three strain rates, 1e-2, 1e-4 and 1e-6 per second. Both materials show a marked reduction in UTS above 700°C and had similar strengths at high temperatures. At 800°C and above the monotonic tensile responses of the two materials were dominated by creep.

CNR studied the uniaxial creep behaviour of C263. Constant and variable load creep tests were run on cylindrical specimens at temperatures from 600-950°C. Some tests on sheet specimens were also performed in order to compare the creep resistance with the cylindrical samples manufactured from bar.

For C263, the experimental results showed the creep curve shape to be strongly dependent on the applied stress and temperature. Primary creep dominated the material response at low temperature but was negligible above 900°C. Sheet material was more resistant to creep at low temperature, probably due to the rolling process, but it showed a lower time to rupture above 800°C. At high temperature significant oxidation of the specimens was observed, but not sufficient to explain fully the observed differences in behaviour between sheet and bar materials. The strains to rupture were similar at 600°C, much higher for sheet at 800°C but lower at 950°C.

Variable load creep tests were also performed on C263 bar specimens to establish the validity of the assumption (Robinson's rule) that the sum of the fractions of creep life used up at different loading conditions should equal unity when failure occurs.

A pre-study of H230 behaviour made by APS indicated significant differences in behaviour between virgin and aged material, and the test matrix therefore investigated both conditions. Stress relaxation/block loading constitutive tests were also performed on H230.

RR performed tension-torsion creep tests on C263 using tubular specimens with a 1 mm wall thickness. The relative amounts of axial and torsional load applied to the specimens were varied to keep the von Mises stress constant whilst achieving the following five loading types: axial tension, equal axial tension and torsion, pure torsion, equal axial compression and torsion and axial compression. The results exhibited significant scatter, and the compression-torsion and pure compression results were less reliable due to specimen buckling. However, the equivalent strain rates clearly reduced as the test conditions moved away from uniaxial tension. The Levy-Mises flow rules were shown to hold for C263, with the creep strains being in the same ratio as the deviatoric stresses. An effective stress formulation was successfully used to describe the rupture lives.

Plain specimen strain controlled isothermal fatigue tests were performed on both materials at 300, 600, 800 and 950°C. Four basic loading cycles were used, plastic-plastic (pp), creep-plastic (cp), plastic-creep (pc) and creep-creep (cc) waveforms. The letters refer to the dwell periods in the tensile and compressive parts of the loading cycle respectively. p-type cycles had a 0.2s dwell and c-type cycles had a 10s dwell. 0.2s loading and unloading ramps were used for all cycle types.

The majority of tests were performed at an R-ratio (min/max strain) of –1. Data were also generated, however, at R-ratios of 0 and –infinity (pure tensile and pure compressive strain).

CNR performed the baseline strain controlled LCF tests in C263 at 950°C. The results showed consistent behaviour, with the fast (pp) cycle having the longest endurance, the tensile and compressive dwell (cc) cycle the shortest and the cp and pc cycles between these. The strain R ratio had only a minor influence on the stabilised test stresses and therefore a limited effect on life. R ratio effects were also insignificant in the lower temperature tests performed by QQ and RRD.

CNR additionally completed isothermal strain controlled LCF tests in vacuum. Experimental lives in vacuum were consistently higher than in air, indicating the important role played by oxidation in crack initiation. Although outside the scope of CPLIFE, this work highlighted the requirement for quantitative models to predict the effect of oxidation on component life.

Following observations from the TMF tests, RRD performed LCF tests at intermediate temperatures on both aged and unaged material. Ageing was found not to influence the fatigue life under isothermal conditions, although the stress-strain responses were very different with unaged material experiencing more inelastic deformation and hardening significantly to a similar stabilised condition.

TM and APS tests on H230 revealed significant cyclic hardening at low temperatures that made it difficult to identify a stabilised hysteresis loop for life calculation purposes. For H230, the test results at high temperature were found to fit on one curve when life was plotted against inelastic strain.

In addition to creep, tension-torsion fatigue tests were also performed on thin walled tubular specimens by QQ. For a given test temperature and equivalent stress condition, biaxial tension-torsion loading and uniaxial loading were both more damaging than pure torsion loading. From a fracture mechanics standpoint, the difference in fatigue behaviour in the three stress states could be explained by assuming that there is a larger principal tensile stress component in biaxial and uniaxial tests than in torsion. This tensile stress would assist fatigue crack opening and therefore decrease fatigue life.

Laser drilling of the featured LCF specimens in both materials was carried out by RR. The SEM examination of one of the angled laser drilled holes by QQ found sputtered edges with cracking of the recast zone and approximately 50µm cracks at the surface at the high Kt corner on the laser beam entry side of the test piece. Examination of the 90° hole specimens indicated cracking of the recast zone within the holes, although no apparent cracks were found that penetrated the specimen ligament.

In the C263 featured specimen LCF tests, all of which were carried out by QQ, fine-gauge platinum wires were spot welded above and below the 0.7 mm diameter hole to monitor the increase in potential drop across the notch as the crack initiated and grew. A series of PD calibration curves were generated using finite element methods. This allowed both crack initiation life and crack propagation data to be produced during the tests. APS and TM performed corresponding tests on Haynes 230.

RR performed crack growth tests on C263 at 300 and 600°C. Higher growth rates were observed at both temperatures for cycle waveforms with higher mean stresses. There was also a small dependence on the applied stress level. The results were successfully correlated using a Walker correction. There were no clear thresholds in the data at both 300°C and 600°C, the results appearing to follow the Paris law from relatively low ΔK values.

QQ carried out corner crack propagation tests on C263 at 800°C under R=0 and R=-1 conditions. The four loading conditions investigated for isothermal plain specimen LCF were used, namely plastic-plastic (pp), creep-plastic (cp), plastic-creep (pc) and creep-creep (cc) waveforms. As before, p-type cycles had a 0.2s dwell and c-type cycles had a 10s dwell. 0.2s loading and unloading ramps were used for all cycle types. None of the crack growth curves was influenced by the applied peak stress level. The fatigue crack growth rate increased due to the application of a dwell period at peak load and for of a dwell period during the compressive part of the cycle. This signified that both oxidation and creep were promoting an increase in crack growth rate.

MTU carried out crack propagation tests on H230 material.

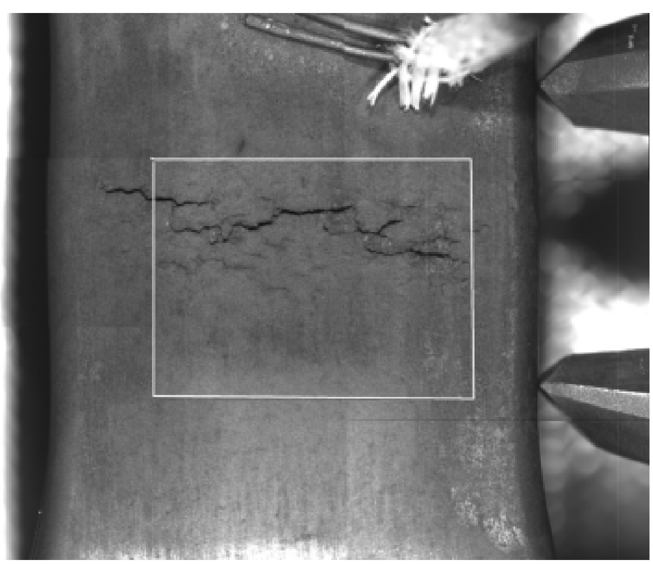
Two types of TMF loading cycle were defined in Task 4.1 for the tests to be carried out at EC-JRC-IAM. The cycle of most interest corresponded to a combustor hot spot, and had a temperature change from 300-950°C imposed out of phase with the applied mechanical strain, which was compressive throughout. The second type of cycle related to a cooler area of the combustor, and had a strain applied at an R ratio of 0 in phase with a temperature variation from 300-850°C.

EC-JRC-IE carried out TMF tests on plain specimens in air and vacuum for both materials. A further series of tests using specimens with 90° and 20° holes were also completed.

Contrary to expectation, the plain specimen TMF lives recorded in vacuum for both materials were consistently lower than in air. This was attributed to a poor temperature distribution in the gauge section of the vacuum specimens.

The tests performed using an R=0 in-phase loading cycle lasted longer at the same strain range than the R=-infinity out of phase tests. Haynes 230 had slightly better plain TMF strength, but the featured specimen results for both alloys were very similar. The test pieces containing laser drilled holes angled at 20° to the specimen surface had the highest elastic stress concentration factor and produced the lowest lives.

Some of the JRC TMF testing was monitored by a video camera. An example of a video image is given in Figure 3. Crack development during these tests was analysed in detail.



Cracking of JRC TMF test specimen a few cycles before failure **Figure 3**

MTU performed TMF tests on Haynes 230 material in the temperature range 350°C to 700°C with a phase shift of -90° and heating and cooling rates of 5K/s (triangular waveform). These results were compared with data for more realistic tests where the strain-temperature path was adapted to the calculated rig cycle. This resulted in a four part loading cycle with different heating and cooling rates in each ramp. The realistic cycle shape had a shorter life at lower strain ranges and longer life at higher strain ranges.

Task 3: Materials Behaviour Modelling

Materials models were developed to allow improved component stress analyses to be performed and to make estimates of both the number of cycles required to initiate fatigue cracks and for them to grow to cause structural failure. The baseline and sensitivity specimen tests were used to determine parameters for the models, which were subsequently tested by comparing the predicted behaviour in the more complex verification tests with the experimental results. The models were then used to simulate the behaviour of the rig test components.

Task 3.1: Deformation modelling

The key requirement from the deformation models was to be able to predict the material stress-strain behaviour for both the first loading cycle and when stabilised conditions had been reached. Parameters such as strain range, peak stress etc. were then taken from the simulations and used to calculate cyclic life.

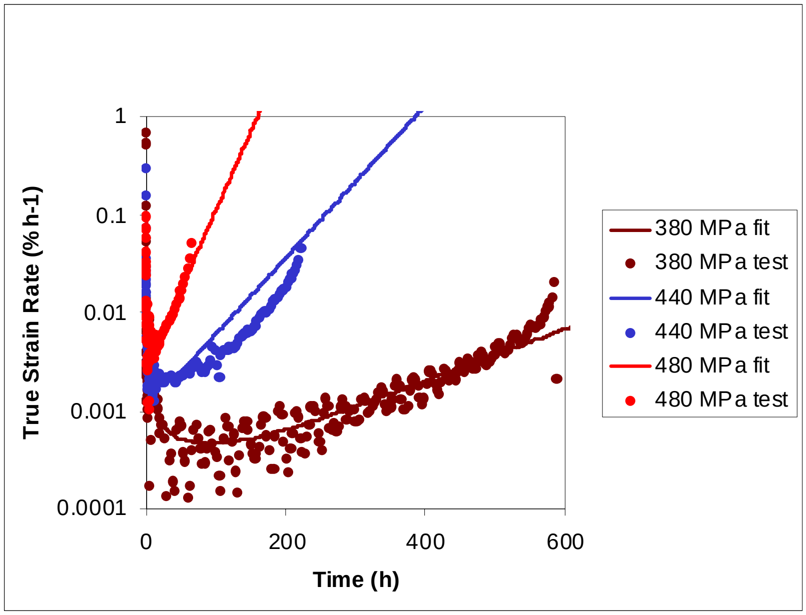
Accurate predictions of stresses and strains required equations to be developed that described the inelastic behaviour of the material across all temperatures. Two types of approach were used by the partners, the first of which involved the separate characterisation of creep (high temperature, time dependent deformation) and plasticity (low temperature, time independent deformation). The alternative unified approaches, principally developments of the Chaboche model, treat all inelastic deformation as being equivalent and have one set of equations to characterise behaviour at all temperatures.

RR followed the classical modelling route and first carried out fits to the stress rupture and creep data for C263 produced by CNR. The representation of test behaviour was excellent at intermediate temperatures but less good at modelling the different creep curve shapes seen at high and low temperature extremes. RR also determined the parameters for the Mroz multi-layer plasticity model for both fully aged and non heat treated C263 material. The combined creep-plastic representation of material behaviour was implemented as a *UMAT user material subroutine for the FE program ABAQUS and in the Company's in-house FE code SC03. Good quality simulations were made of the behaviour of tensile tests at different strain rates and stabilised stress-strain responses in isothermal LCF and TMF.

The main objective of the deformation modelling work being carried out by CNR was to develop a physically based continuum damage mechanics (CDM) approach to model the creep behaviour of C263. The model developed includes material recovery and creep strain softening effects. To describe the temperature dependence of the parameters, three different intervals were taken into account: low temperature (600°C), intermediate temperatures, below the solvus temperature of the reinforcing γ'phase (700-800°C) and high temperatures where the γ' volume fraction starts decreasing (around 900°C) until it is completely in solution (around 950°C). Inside these intervals an Arrhenius temperature dependence of the parameters was supposed. Strain rate predictions for different tests performed at 700°C are shown in Figure 4.

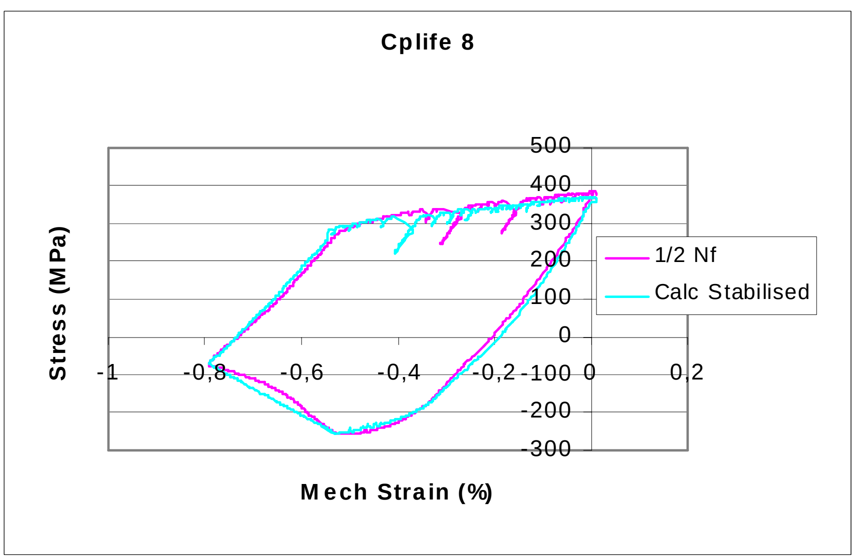
QQ used both classical and unified deformation models. The classical approach used the QQ creep law with monotonic and cyclic stress-strain curves analysed using the Ramberg–Osgood expression. A Chaboche-style unified model was developed.

Problems were encountered with the QQ creep data analysis software that limited the application of the model to 700 and 800°C. Good correspondence was found between the predicted and experimental data at these two temperatures. The ABAQUS combined hardening plasticity model was applied to simulate the isothermal strain controlled C263 LCF tests at R = 0 and –1 under the pp loading cycle at 300°C. Generally good predictions were found, although the approach could not be used in conjunction with a creep model. Significant effort was therefore put into developing a Chaboche type model. The isothermal LCF loop simulations produced via this approach were very good, although the model tended to over-estimate the material strength in TMF. Further work was therefore carried out to obtain a parameter set from LCF tests conducted on un-aged C263 specimens.



CNR creep law strain rate predictions, C263 bar at 700°C **Figure 4**

SENER fitted parameters to the Bodner-Partom model for C263 and H230 materials. This model was implemented in ZEBULON and used to simulate stress responses under isothermal and TMF loading conditions for both materials. An evaluation of the ABAQUS combined hardening model was also made for both materials. A variety of LCF tests were simulated using these models. Although the calculated values of maximum and minimum stress were reasonable, the shape of the calculated isothermal hysteresis loops was too angular. The TMF simulations, however, agreed closely with the experimental data as shown in Figure 5.



SENER prediction of stabilised stress-strain response in C263 out of phase TMF test with 0.8% strain range using the Bodner-Partom deformation model **Figure 5**

RRD initially proposed to develop a unified 24 parameter Chaboche model for C263 including isotropic and kinematic hardening equations, where the asymptotic value of the isotropic hardening terms depended on the whole loading path history. Initial assessments of the specimen test data, however, showed no history dependence in the isotropic hardening and therefore a simpler 9 parameter model was adopted. This was modified to include the Ohno-Wang equation for kinematic hardening and a term representing ageing effects. The final Chaboche model was able to predict the stress-strain loop shapes, minimum and maximum stresses and hysteresis loop areas well under isothermal LCF and TMF conditions.

The deformation model developed by APS for H230 was made up of three parts, an elastic-ideally-plastic model below 550°C with two virgin and mid life material properties together with a simple creep model above this temperature. It was not considered necessary to model the back stress and work hardening behaviour. The model was implemented in ABAQUS and used in conjunction with the following calculation procedure, after which it was assumed that a stabilised cycle has been reached: two simulation cycles with virgin material properties, one with mean virgin/mid life properties and two cycles with mid life properties. Good agreement was obtained using this method of the material response through different constitutive test cycles.

The MTU deformation model contains separate plasticity and creep terms and is based on the theory developed by Wetzel. The plastic behaviour is represented by a Ramberg-Osgood expression where K and n are assumed to vary with cycle number. The creep equation describes the secondary creep behaviour. This approach was used to simulate the stress-strain response in H230 isothermal strain controlled LCF tests. To allow the model to be applied to TMF loading, the discrete numerical constants fitted at the available test temperatures were expressed as functions of temperature.

TM modelled the deformation behaviour of Haynes 230 with the ZEBULON software, using parameters determined from isothermal LCF, creep, stress relaxation and tensile tests. This task proved difficult with the Chaboche viscoplasticity models and the corresponding fitting tools available within ZEBULON, mainly because the very strong cyclic hardening at low temperature prevented both the initial and stabilised hysteresis loops from being modelled correctly. At 800°C this hardening became less significant, but LCF loops and relaxation tests with longer hold times could only be approximated using a complex double Norton flow model. The great number of coefficients required for reasonable accuracy across the required temperature range were considered to be a major drawback of this approach, especially for actual finite element calculations on real components.

Task 3.2: Crack initiation modelling

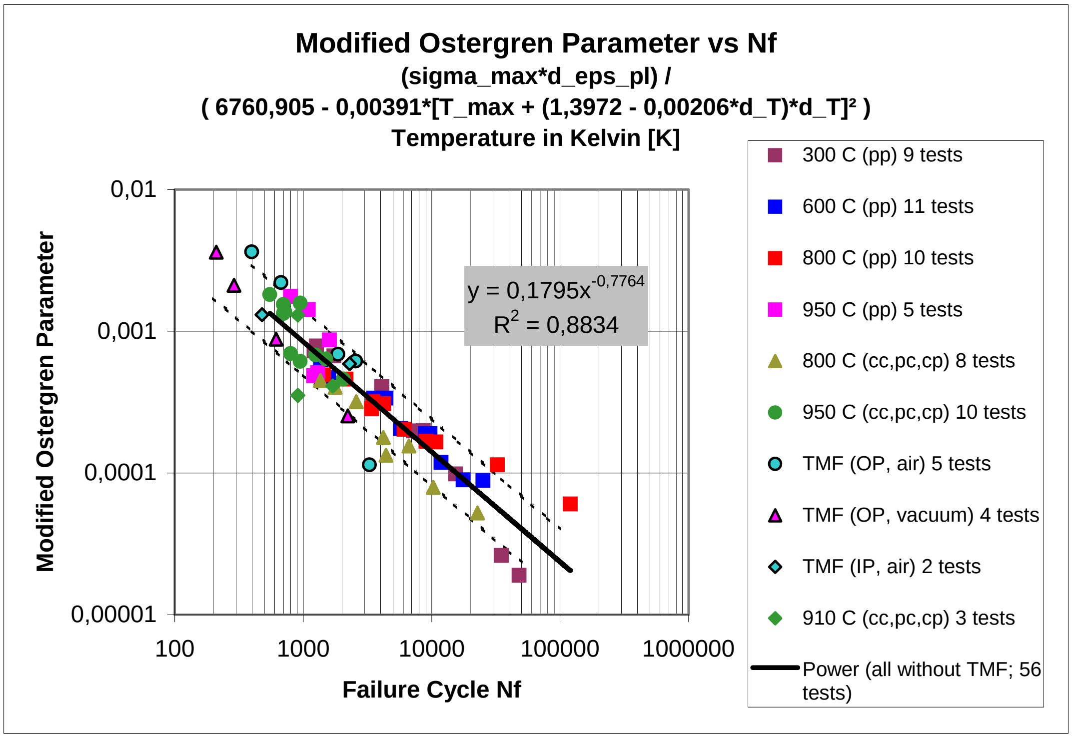
Parameters for the crack initiation models were determined using results from isothermal strain controlled LCF tests. The models were then applied to increasingly complex test types from plain TMF through featured specimens to the rig components.

The majority of the fatigue life of plain specimens is spent in initiating cracks, with the propagation phase typically representing only 5-10% of life. The use of cycles to failure from plain specimen tests to correlate initiation lifing parameters was therefore seen as a reasonable approximation. For featured specimens the balance was expected to change, with initiation becoming less important as the stress concentration factor increases.

The Walker strain model adopted by RR to characterise initiation life proved successful in correlating all of the isothermal LCF results. The parameter is based on the maximum stress and strain range from the stabilised hysteresis loop. Unlike previous work on disc alloys, however, the parameter did not collapse the results from tests at different temperatures onto a single curve. TMF lives were reasonably well predicted using the Walker strain parameter at the 300°C minimum cycle temperature and the 950°C lifing curve. It had been anticipated that the TMF lives could be predicted entirely from the 300°C data, but this was not possible because TMF cycling reduced the material to an unaged condition and the 300°C isothermal lifing data included the benefits of ageing.

ALSTOM showed that the isothermal fatigue behaviour of H230 subjected to different loading cycles at 800 and 950°C could be correlated using the inelastic strain range. Extension of this approach to TMF, however, using LCF data at the peak temperature in the TMF cycle, gave non-conservative life predictions because the embrittlement caused by high temperature exposure is only significant when loading at low temperature. This mechanism therefore affects the life of TMF specimens (and components) in a way not experienced in isothermal testing. APS's preferred approach is therefore to calculate component lives based on TMF results.

RRD applied various lifing parameters based on saturated stress-strain hysteresis loop information to correlate the isothermal Low Cycle Fatigue (LCF) data for C263 over a wide temperature regime and with different loading cycles. Frequency dependent functions were included in the parameters. It was concluded that the Plastic Strain Range, Plastic Walker Strain Range and Modified Ostergren parameters were the most promising for high temperature fatigue lifing of C263. These approaches were able to predict almost all the isothermal strain controlled LCF test lives within a factor of 2 as shown in Figure 6. Most of the out of phase TMF test data in air and vacuum also lay within this life scatter band, while the rest of the TMF results were below the lower bound.



RRD plot of modified Ostergren parameter against life for C263 LCF and TMF tests Figure 6

The crack initiation work for plain specimens at QQ comprised two principal activities. In the first, the available isothermal fatigue data on C263 were analysed using the Smith-Watson-Topper parameter (SWT). SWT correlated well with the test data at 300 and 600°C but was slightly less successful at 800°C due to the influence of creep. At 950°C the material has a different microstructure, reflected by a significantly steeper gradient in the lifing curve. The second activity covered modelling of the multiaxial testing of C263. The data were analysed using stress-based, strain-based and critical-plane strain energy-based multiaxial fatigue models. The use of both maximum principal stress and effective stress criteria produced correlations with significant scatter and was unable to resolve the differences in life experienced for the three types of loading. The energy-based models (Varvani-Farahani and Glinka) produced slightly better correlations with the experimental data but could still not be used for design purposes without employing large safety factors.

The SENER activity in crack initiation modelling used the Strain Rate Partitioning method (SRP). The technique involves partitioning the inelastic strain into different modes, and assigning a damage parameter and associated life to each of the modes. Two types of inelastic strain components are recognised by the SRP method, creep and time independent plasticity. The SRP method was applied to the stabilised loading cycle. For TMF, creep rates were evaluated using a Norton law through the cycle. Application of the method to multiaxial loading conditions required the use of triaxiality factors related to the ratio of hydrostatic stress and effective stress. For life evaluations the sign of the largest principal stress was associated with the effective stress and strain values.

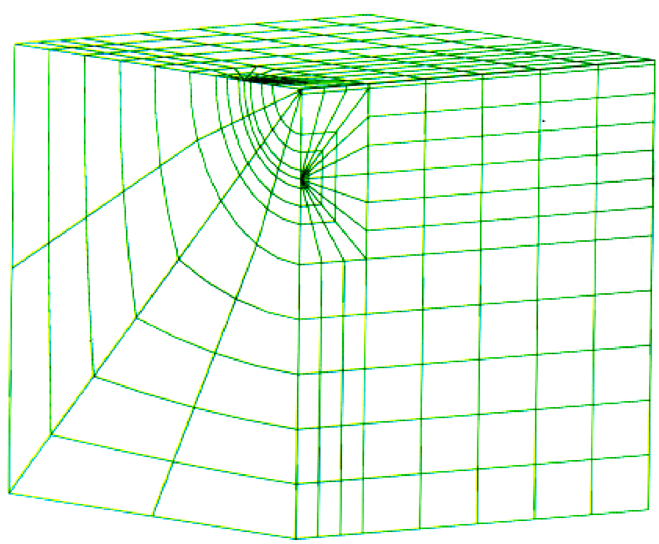
SENER fitted SRP parameters for both C263 and H230. As expected the quality of the fit improved with increasing inelastic strain range. TMF behaviour could not be predicted on the basis of the isothermal test results and therefore these data were used in the parameter fitting process. Most of the isothermal and TMF data could then be predicted within a factor of 2 on life. A major disadvantage of SRP, however, is that a large amount of data are required to derive the life relation curves for the four damage mechanisms at each temperature. The method was implemented as a FORTRAN subroutine that reads results data from ABAQUS and plots the calculated lives using PATRAN. The subroutine was subsequently used to predict initiation lives for the featured specimens.

MTU used a crack initiation approach based on the Wetzel model that was modified to account for temperature variations in non-isothermal loading cycles. The TMF life prediction was based on LCF data at various stress ratios. The total damage was calculated incrementally as a linear combination of TMF and creep terms in each loading step. The underlying database consisted of plain strain controlled LCF results performed by MTU and TM, most having a stress R-ratio of –1. Goodman diagrams were constructed to read these results across to other R-ratios. The approach gave conservative predictions of the lives of OOP TMF tests. Standard lifing procedures using a mean stress corrected strain range at the maximum cycle temperature gave optimistic results.

FIAT was an end user of the crack initiation methods. In preparation for their prediction of the life of the TM rig test combustors a limited amount of data fitting and specimen life calculation was performed using models from other partners and test data generated by TM.

Task 3.3: Crack propagation modelling

QQ performed FE analyses on the corner crack test piece geometry shown in Figure 7 to determine the stress intensity factor K different crack sizes. This work was also extended to calculate the J-Integral for elastic-plastic fracture and the C* integral for creep crack growth using a simple Norton creep model. Both ABAQUS and the specialist fracture mechanics FE code ZENCRACK were used for the analyses.



'Quarter-penny' crack model used by QQ to analyse the C263 crack growth test results Figure 7

Initial attempts to evaluate the influence of temperature, R-ratio, waveform and dwell periods on crack propagation behaviour were based on the linear elastic fracture mechanics (LEFM) parameter K and the Paris crack growth equation. To account for the effects of R-ratio, both Elber and Walker correction methods were used successfully to correlate the results. Methods used to model the crack growth behaviour at high temperature were based on either factoring the pp data or using a linear summation of time dependent and time independent crack growth terms to account for dwell effects. In general, reasonably good correlations of each model's predictions with the test data were obtained.

The QQ crack growth models were verified by comparing predictions for the featured specimens with a 90° hole with experimental measurements. Integral to the work performed was FE modelling of the specimen to enable crack lengths and stress intensity factors to be determined from raw experimental data. Direct comparison of the calculated geometry correction factor for the featured specimen with the established Newman solution showed good agreement.

Task 3.4: Efficient FE modelling techniques

A potential problem with the deformation modelling approaches being developed lies in the high run times and associated computer cost required in the finite element routines before stabilised stress conditions are reached. SENER was in charge of the investigation of novel ways of reaching shakedown by running the analyses through a limited number of modified component loading cycles. Two approaches were investigated. The first involved evaluating the ZSET software developed by the Centre des Matériaux de l'ecole des Mines de Paris and NW Numerics in Seattle, USA. This work was funded by SNECMA, who agreed the distribution of the code to SENER. The second approach was based on the power law that can be developed between the stress amplitude and the strain amplitude for the stabilised loading cycle.

Several LCF tests were simulated using the cycle-skip method implemented in ZSET. Although the method did allow run times to be reduced, there was a corresponding drop in accuracy of the results. It was also found that the method relied on accurate deformation models if high stress errors were not to be accumulated. The second approach was shown to work well for known loading cycles but was difficult to extend to other conditions. Overall, further work remains to be done before efficient FE methods can make estimates of stabilised material behaviour that are accurate enough to be used in component lifing calculations.

Task 4: Component rig testing

The rig tests in this programme formed an essential part of the lifing model verification process and were designed to be as representative as possible of engine operation. The initial activity in Task 4 was therefore to understand, via FE analyses, the stresses and temperatures experienced by components. The remaining activities covered the design, manufacture and execution of three different types of component test aimed at reproducing these conditions at a fraction of the cost of running a cyclic test on a complete engine.

Task 4.1: TMF cycle definition

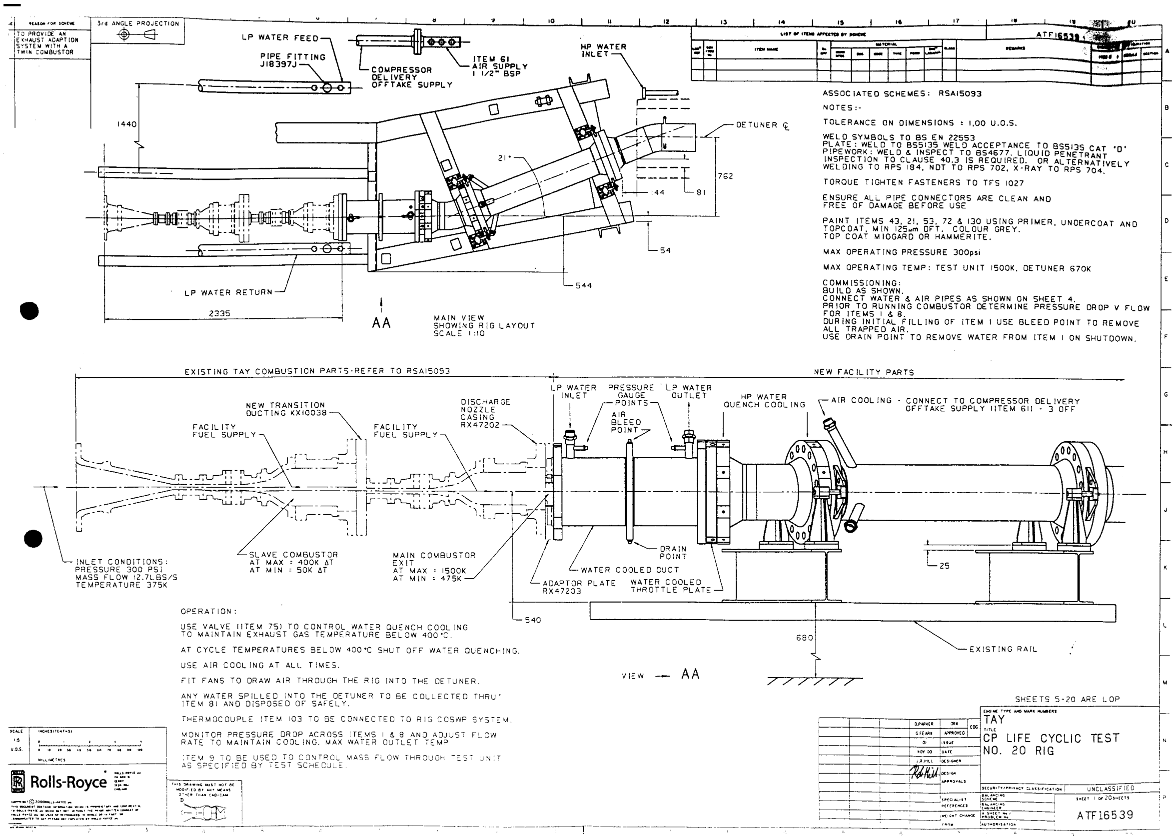
Analyses performed by RR, RRD, TM and APS showed that mechanical integrity problems in combustors were most often associated with 'hot spot' locations that experienced compressive thermal stresses at high temperature. Typical peak temperatures in each case were around 950°C, and transient effects were shown to be insignificant. Mechanical integrity problems caused by tensile stresses had also been observed in lower temperature regions. This information was used to define relevant temperatures for the specimen test programme, phase angles for the TMF cycles and design the component rig tests.

Inclusion of the MTU turbine exhaust casing work in the programme was important to demonstrate that the combustor stressing and lifing models are equally applicable to casings. Heating and thermal expansion of the exhaust casing struts, which sit in the hot gas path, were calculated to cause high bending stresses around the change in section where they join the inner and outer casings. The peak strains in both tension and compression occurred at a transient condition at 500°C, with the maximum component temperature being 700°C. The TMF tests performed by MTU were based on this cycle.

Given the results outlined above, two basic cycles were agreed for the TMF testing at JRC. These were out-of-phase from 300-950°C at R=-infinity to represent a combustor barrel hot spot, and in-phase from 300-850°C at R=0 for cooler areas.

Tasks 4.2-4.4: Component rig tests

The RR rig used two combustors in series, a slave unit that acted as a pre-heater and the main test unit containing four patches of angled effusion cooling holes. This ran at a design pressure of 20 bar to achieve representative heat transfer conditions, with a constant air inlet temperature to the slave combustor of around 100°C. Both combustors were lit throughout the test, with fuel flows just above the weak extinction level at the cycle minimum point and representative of engine maximum conditions at the top end of the cycle. This allowed the metal temperatures in the region of the effusion holes to be varied from 300°C to 950°C and back in an 80s cycle that included a 30s dwell at maximum conditions. The rig layout is shown in Figure 8.



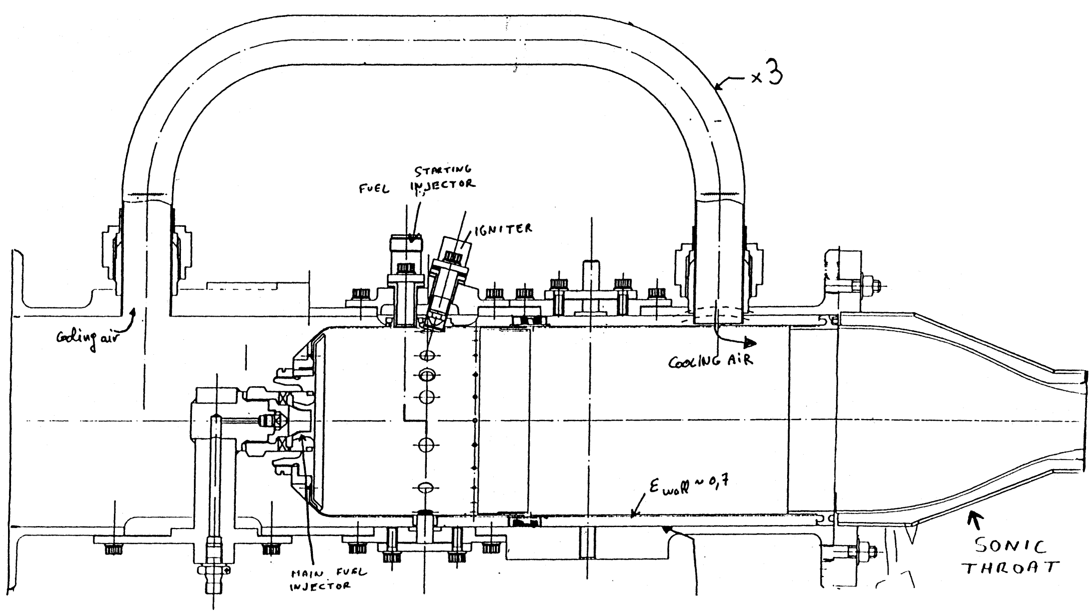
Design scheme for RR rig test **Figure 8**

The rig concept was demonstrated by a feasibility test early in the programme. The detailed design work was then carried out for the rig, control system and test combustor. The test combustor was manufactured and run with thermal paint to check the peak metal temperature distribution. Following the addition of further cooling holes and a second thermal paint test the metal temperatures were considered to be acceptable.

Rig build and commissioning were large tasks involving manufacture of mountings for the rig hardware, installation of fuel, water and air systems and new rig control panels. The control software was also developed and installed during this period. 656 cycles were completed on the rig, with the performance of the control system being gradually optimised throughout, before testing was halted by water leaks from cracks in the throttle plate and the water cooled duct. The components were repaired, pressure tested and re-assembled. An additional 282 cycles were then performed, making a total of 938. Further running was not possible, however, due to more water leaks. Detailed examination of the rig revealed cracks in a number of the rig facility components, the throttle plate, the adapter between the test combustor and the water cooled duct, the thermocouple boss on the water cooled duct and two areas on the wall of the water cooled duct. The test combustor remained uncracked, based on an in-situ inspection. After considering the anticipated repair costs and associated delays, it was decided that no more rig running would be possible in the CPLIFE programme. The performance of the RR rig had therefore been demonstrated successfully, although no cracks in the combustor had been produced that could be used to verify the lifing models.

The TM rig tests, as shown in Figure 9, used a single tubular combustor made of H230 featuring cooled zones with holes to induce high thermal stresses. Local cooling was achieved by taking low temperature air from upstream of the combustor via three pipes and directing it onto the test section. The test section was located to the rear of the combustor head and contained three different stress concentration features, a large diameter dilution hole and two patches of smaller effusion holes angled at 30° and 90° to the surface of the combustor. In order to give the required thermal gradients, a sonic throat at the combustor exit was used to generate an internal pressure of 5 bar.

RIG TEST GLOBAL VIEW

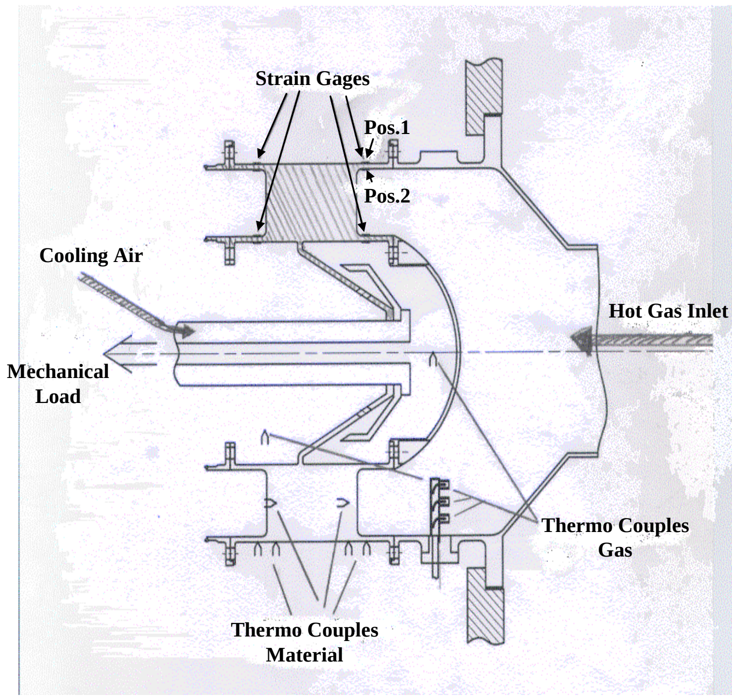


Diagrammatic view of TM rig test layout **Figure 9**

A number of problems were experienced initially with the rig, including high vibration and noise levels and combustion instability. These were resolved and, following a thermal paint test, the first of the planned three cyclic tests was run. The test combustor failed by buckling, however, upstream of the features under test. It was therefore decided to increase the sub-element wall thickness to 1.25 mm from 0.8 mm. Whilst new test combustors were being manufactured, a second test was run on a combustor to the original geometry standard. This also failed prematurely, caused by misalignment of the film cooling just upstream of the sub-element.

Two thermal paint tests were run on the new geometry at less severe thermal conditions, the first being unsuccessful following an overtemperature. 5000 cycles of four minutes duration were run at these conditions, after which the test combustor was uncracked. As for the RR rig, therefore, no datum point for model verification was produced by the TM test.

The MTU rig test in Figure 10 used a model turbine exhaust casing (TEC) made from Haynes 230 material. The structure consisted of inner and outer casings joined by eight struts with a rearwards mechanical load applied to the centre of the TEC by a hydraulic mechanism. Air was constantly heated up in a combustion chamber and directed through the gas duct of the TEC. A cyclic temperature variation was achieved by mixing in appropriate amounts of cold air. This generated high stresses in the critical areas of the component, the leading edges of the struts at the outer diameter.



MTU rig test arrangement showing thermocouple and strain gauge positions Figure 10

To calibrate the mechanical axial load, a room temperature test was performed. Strain gauge readings at the critical locations showed acceptable agreement with results from an FE simulation. The thermal FE analysis was calibrated in a similar way by comparison with thermocouple measurements.

Based on MTU's specimen TMF results, the rig test life to crack initiation was predicted to be 2900 cycles. Accordingly, the rig was inspected for the first time after 500 cycles. Cracks were observed in the expected critical locations. The test was then continued for a further 300 cycles, inspecting the TEC after each increment of 100 cycles.

Task 5: Model verification

In this Task, the stressing and lifing models developed in Task 3 were used to predict the results of complex tests on specimens containing laser drilled holes and rig test components.

Finite Element calculations of the temperatures and stresses in the rig test components were carried out in an identical way to that for designing full size engine hardware. The materials models were used to predict highly loaded areas on the components under test and their cyclic endurance. RR and MTU performed thermal and stress analyses on their own rig test components. Analysis of the TM tests was carried out by FIAT.

Task 5.1: Mesh Density Sensitivity Studies & Featured Specimen Analyses

SENER carried out work to evaluate the effects of mesh density on the results obtained from FE models of the angled hole specimens. The objective of this task was to allow the optimum mesh density for further analyses to be determined, giving accurate results whilst minimising analysis time. It was found that the analysis time required increased as the square of the model complexity, whilst the error decreased exponentially. Results from this were used to define appropriate mesh densities for both featured specimen designs.

As the interim step in verifying their deformation and lifing models for component analyses, a number of the partners made life predictions for the featured specimens

RR used a combined crack initiation and propagation approach to life prediction. Stabilised stresses and strains at the critical locations of the two featured specimen designs were calculated non-linearly through ten loading cycles in the FE code SC03 using the Mroz plasticity model and RR creep law. Initiation lives were predicted using the peak Walker strains calculated from the FE analyses in with the plain specimen life curve. Propagation lives for each specimen were calculated by subtracting these initiation lives from the number of cycles recorded to failure. Linear elastic fracture mechanics (LEFM) calculations were then performed to determine an effective initial flaw size (EIFS) for each test assumed to be present in the material at the end of the initiation period. EIFSs were found such that the crack would grow from the EIFS to reach the material's fracture toughness in the calculated propagation life. A single EIFS, the mean of the values from the individual tests, was then used for all life predictions. This approach allowed all the 300°C results to be correlated successfully, and the 800°C results for both specimen geometries followed similar trends with the lives being under-predicted at lower applied stresses. This suggests that the combined initiation plus propagation lifing approach is valid but further work is required to improve the quality of the initiation fit at 800°C.

APS also attempted to verify the predictive capability of their constitutive and life models developed on the basis of H230 smooth specimen data by applying them to notched specimens. A significant problem, however, was that the APS constitutive model was targeted at TMF loops with long hold times whereas the CPLIFE LCF and TMF tests were run without hold time and at significantly higher strain rates. Simulations were made, however, using a plasticity model. The predicted crack initiation life for the LCF tests with 90° holes at 600°C and 800°C, as given by the stabilised inelastic strain range from the simulation and smooth specimen LCF data, was between 2.5 and 10 times lower than the measured number of cycles to separation. This was considered to be reasonable.

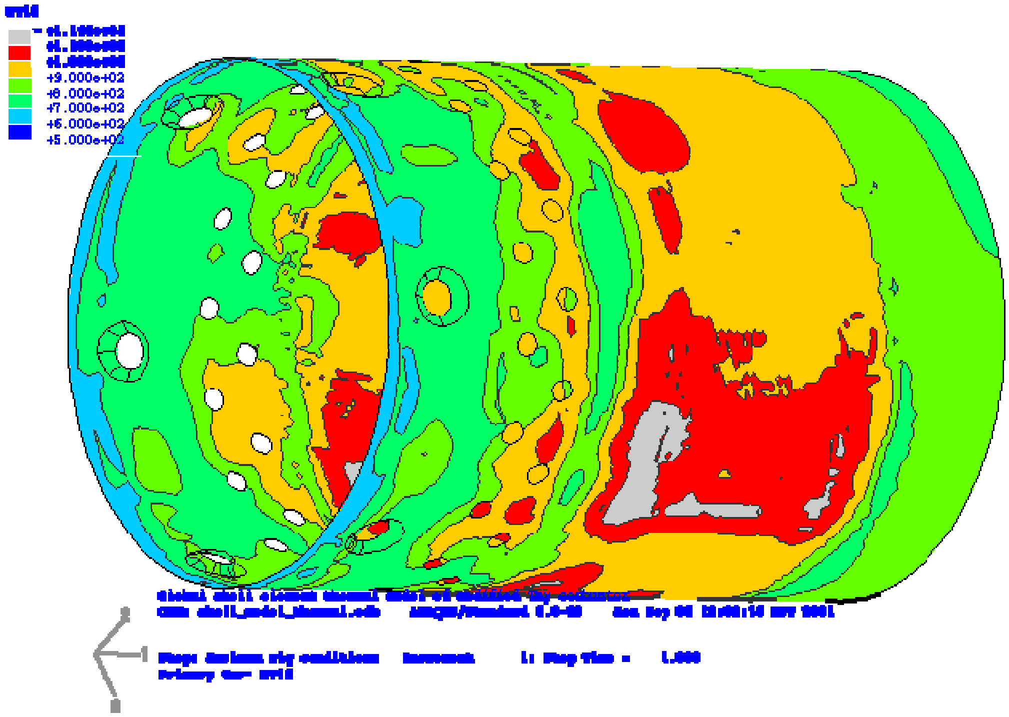
SENER analysed all of the C263 featured specimens using both the Bodner-Partom deformation model and the combined hardening model implemented in ABAQUS. Lives were calculated using the SRP method. The predictions, however, were always conservative and not as good as had been anticipated. Potential sources for the discrepancy were considered to be inaccuracies in the high temperature deformation model when extrapolated to high stress ranges and the high stress (and hence life) gradient observed in the featured specimens. The life predictions could therefore have been improved by taking stress-strain parameters a reference distance below the surface of the specimen rather than peak surface values. In general, the predictions for the 90° hole were better than for the 20° hole. This reinforces the opinion that predicted failure at the most highly stressed integration point of the FE model does not correspond to initiation of a real crack in a featured specimen.

RRD also applied its calculated initiation parameters to predict the featured specimen lives. The FE analyses used the RRD Chaboche model. The life predictions for the 90° hole specimens were mostly within a life scatter band of 2.

QQ investigated two versions of the Smith-Watson-Topper (SWT) lifing parameter using both effective and principal stress/strain measures. None of the approaches investigated gave a consistently good prediction of life, however, for different specimens. The predictions based on a uniaxial LCF database were better than those using a multiaxial database.

Task 5.2: Rig thermal FE analyses

To capture both global and local effects, a sub-modelling approach was adopted for the thermal and stress analyses of the RR rig test. The thermal analysis used paint test results image processed onto the global shell model of the combustor in PATRAN. Additional thermal boundary conditions were then added to provide a sensible temperature distribution. The calculated temperatures on the inside of the combustor are shown in Figure 11.



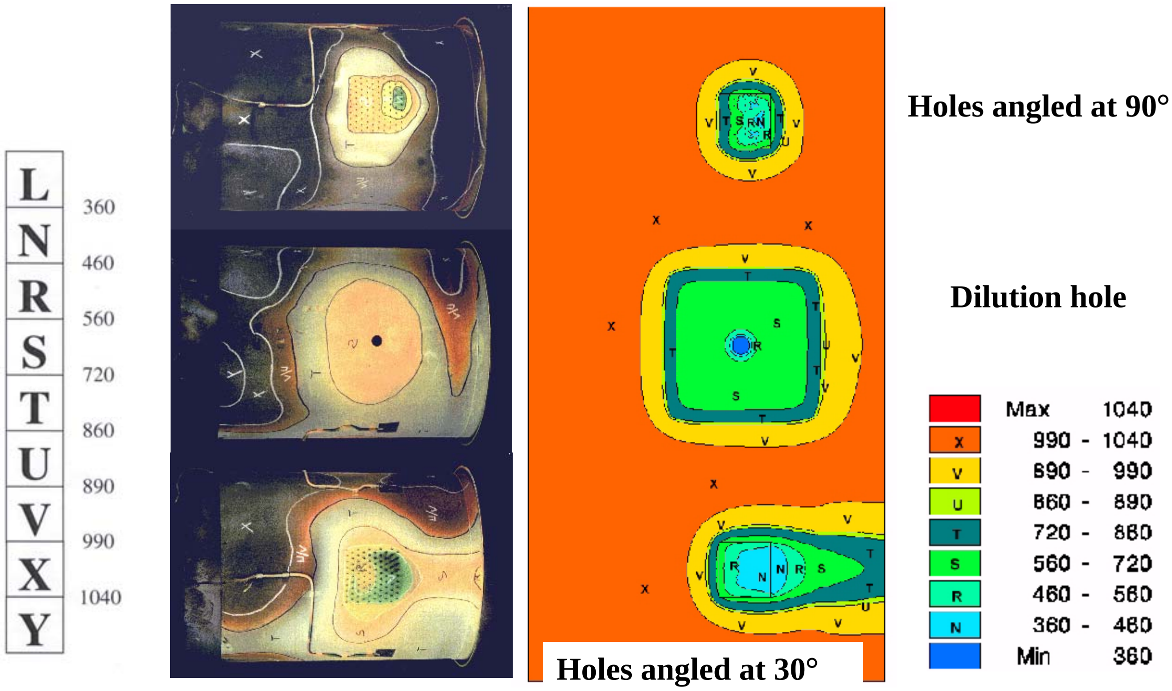
Shell model of RR rig combustor showing calculated hot side temperatures **Figure 11**

Four 3D submodels, one for each of the different effusion cooling patterns, were then constructed in PATRAN. The submodels were positioned in highly stressed regions from the global model analysis. Further convective boundary conditions were applied to the inside surfaces of the effusion cooling holes to achieve realistic local temperature distributions.

FIAT calculated global temperatures for the TM rig tests using a 2D thermal model that accounted for radiation, convection and conduction both in the radial and longitudinal directions. The effect of wall thickness was included in the source term of the balance equation. The model also considered interactions between the three different cooling devices and used a new technique for modelling effusion holes. Comparisons between the thermal paint results and the calculated 2D temperatures are given in Figure 12. A 3D sub-model of the 30º angled effusion holes was also produced. The heat transfer coefficient through the holes was evaluated from standard correlations. Results showed the cooling effect and the through thickness temperature distribution to be reasonable.

Because of the likely importance of transient thermal stresses, MTU performed temperature calculations on their rig component through the full loading cycle. Since the complete test rig had an axial-symmetric test section with a total of 8 struts, it was only necessary to model one 45° segment. Cyclic symmetry boundary conditions were applied to keep temperatures and stresses on the cut faces of the model equal. Three types of thermal boundary conditions were used in the model, corresponding to the three mechanisms of heat transfer – conduction, convection and radiation.

The thermal loading profile consisted of a periodic cycle between two load cases, a heating phase and a cooling phase. The model was calibrated against measured temperatures taken at a few locations. The two primary degrees of freedom in the calibration were the adjustment of correction factors for the heat transfer correlations and the inlet gas and cooling air temperatures. These parameters were tuned until a good match was found between the measurements and computation results over the complete rig cycle.



Early TM rig thermal paint results and 2D temperature predictions from FIAT Figure 12

Task 5.3: Rig structural FE analyses

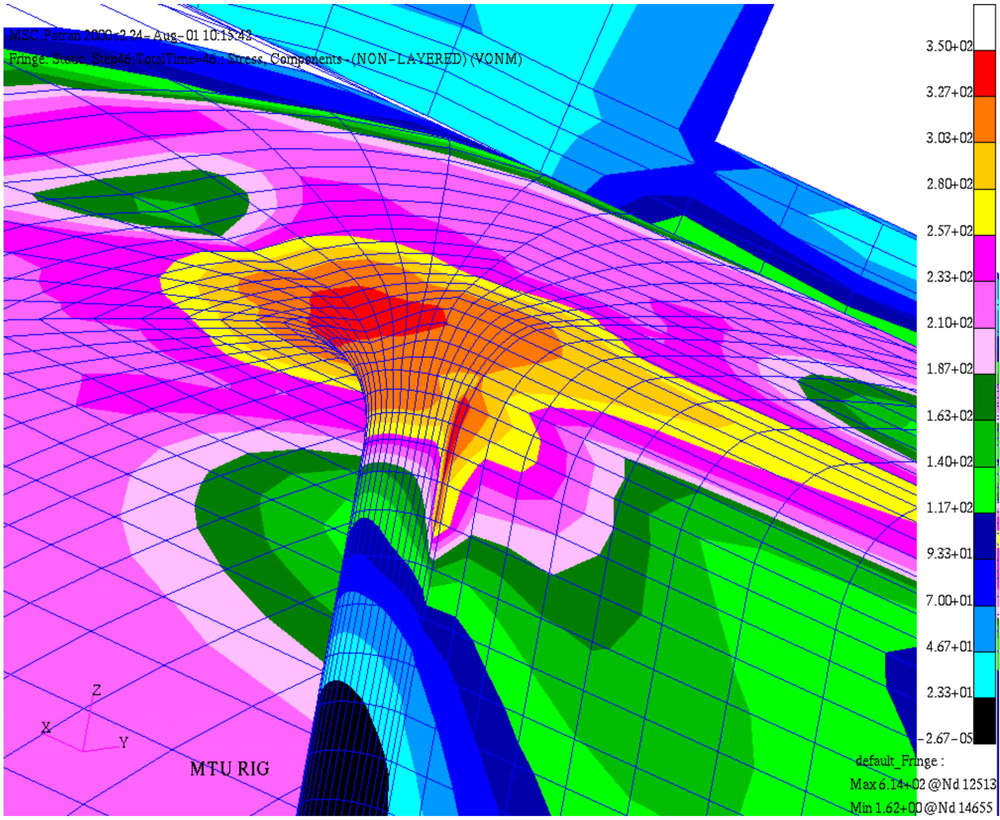
A global shell model of the RR test combustor was constructed as discussed under Task 5.2 above containing appropriate stiffness values for the four test zones with effusion cooling holes. A local 3D stress model of the most severely loaded area of effusion cooling was also produced. Three different external loads were applied to the global model during the stress analysis, the pressure difference between the inside and outside together with an outwards radial force and displacement at the front of the model to represent the head of the combustor. The mechanical load for the sub-model was imposed as displacements from the global model at the interface between the global and sub models.

FIAT performed structural analyses of the TM rig test using predicted metal temperatures. Two FE model types were analysed, the whole combustor and sub-models of the film cooled areas and the dilution hole. Elastic material behaviour was assumed for the coarse global model of the combustor. The sub-model analyses used non-linear stress-strain relationships. The global model of the combustor was made up of 2D shell elements.

Two types of loads act on the combustor, mechanical and thermal. The mechanical load arises from the difference in air pressure between the outside and inside of the can that allows cooling air to pass through the effusion and dilution holes. Thermal stresses arise from local temperature differences and the overall constraints applied to the test section.

The sub-models were analysed using boundary conditions taken from the corresponding regions of the global coarse model under the same loading conditions. Displacements and rotations of the appropriate nodes of the global model were interpolated to the nodes around the perimeter of the sub-models. Thermal loads were applied by interpolating temperatures between the nodes of the global model and the sub-model.

The stresses in the MTU TEC sub-element were calculated based on temperatures from Task 5.2 and using the same FE mesh. Symmetric boundary conditions were applied to both sides of the structure along the cut faces. An axial restraint was applied to the outer diameter front flange. Linear structural analyses were performed using the NASTRAN FE code. Non-linear plastic analyses with assumed isotropic hardening were then performed using ABAQUS. The calculated stresses around the critical feature of the test component are shown in Figure 13.



MTU turbine exhaust duct rig test non-linear stress predictions, 180s cycle point Figure 13

Task 5.4: Life prediction of rig tests

To avoid convergence problems at the interface between the global and the sub model, especially where partially modelled cooling holes were located, QQ divided the sub model of the RR test into an outer rim with elastic material properties and an inner core with visco-plastic material behaviour. A smooth transition of the principal strain component across the interface between the 2D shell elements of the global model and the 3D elements of the sub model was produced. Stabilised stress-strain hysteresis loops at the inner and outer ends of the effusion cooling holes were then calculated and used to determine the Smith-Watson-Topper (SWT) lifing parameter. The critical location on the RR rig combustor was predicted to be the cooler end of the effusion cooling hole with an expected life of 5342 cycles.

The SENER analysis of the RR rig test combustor used a simple isotropic hardening material plasticity model from the ABAQUS library. In order to take into account the hold times at both maximum and minimum cycle conditions it was intended to simulate creep behaviour using a time hardening power law. Convergence problems with the creep algorithm, however, led to the analysis being run with just the plasticity model. The stress-strain loop obtained for the cool end of the effusion hole was used with the Strain Range Partitioning method to calculate a life of 399 cycles. After accounting for triaxiality and mean stress this prediction reduced to 298 cycles. This estimate of life is conservative, since the rig combustor was uncracked after 938 cycles. The principal difference between the QQ and SENER life predictions lay in the calculation of stabilised stresses and strains.

FIAT calculated LCF lives for each of the three cooling devices in the TM combustor based on local strain range and temperature values and a Tmax-Tref cycle. An FE creep analysis was also performed using a Norton model based on results from TM specimen tests. The lifing process was subsequently automated based on user defined subroutines linked to ANSYS. As with the QQ predictions, insufficient rig cycles were run to allow the predictions to be fully verified.

Preliminary calculations performed by MTU resulted in an expected life for the TEC sub-element of 2900 cycles. Following testing and re-calibration of the FE models, life predictions were performed using a number of different analysis procedures. The Wetzel method produced a crack initiation life (to a crack length of 0.8mm) of 496 test cycles at the critical outer diameter leading edge of the struts. The calculation used stresses from a FORTRAN routine based on mechanical strains from the FE analysis and the temperature corresponding to the most damaging strain condition. The experimental crack initiation life was 460 cycles, very close to the prediction. The analysis procedure used by MTU was therefore verified for use in new component design.

4. EXPLOITATION PLANS AND FOLLOW-UP ACTIONS

A description of the specific exploitation activities that will be undertaken by the project partners is presented below:

Rolls-Royce

The CPLIFE results that will be exploited by RR are the improved material understanding, specimen test data, deformation and crack initiation models and the cyclic combustor rig test facility.

The future combustor strategy at Rolls-Royce is based around single skinned components containing a large number of effusion cooling holes. Reducing the risk of premature service failures requires a thorough understanding of the behaviour of these features. This will be achieved through implementation of the materials behaviour models developed in CPLIFE, backed up by representative specimen and component testing.

RR will take the opportunity to re-assess existing designs and their in-service experience using the new methods. The lifing methods will be developed further and used to prepare design curves for components with angled effusion cooling holes. RR will also analyse the H230 results from the programme to investigate its use as an alternative combustor material.

Further opportunities for running the cyclic rig are being explored, including its use to test different thermal barrier coatings, barrel materials and combustor tile designs.

Alstom Power Sweden

During CPLIFE, APS has significantly increased its basic understanding of the carbide precipitating austenitic superalloy Haynes 230, resulting in new constitutive and crack initiation models that can be read across to similar materials such as Hastelloy X. These tools allow new design features to be introduced with significantly reduced risks.

The models will be improved through TMF testing with hold times, including some tests done on pre-aged specimens, to take Industrial Gas Turbine loading conditions into account. This will also include tests on similar materials for ranking purposes. These tests will run during the next two years. Further development of the low cost long term TMF rig is also anticipated to allow the effects of ageing on component life to be assessed.

APS plans to publish details of its constitutive model and slow/fast creep-fatigue test methods to publicise its activities on TMF lifing and improve its ability to form future research partnerships in this area. The publications to date are listed in Section 5.

Rolls-Royce Deutschland

Within the CPLIFE project RRD has developed a modified version of the Chaboche model including ageing effects to describe the deformation behaviour of C263 material. This was implemented as a user material subroutine (UMAT) for the FE code ABAQUS. Crack initiation lifing models for C263 were also produced using various lifing parameters and were correlated to plain specimen LCF data. They were verified using the featured specimen LCF test results. Use of these methods in the engine design phase will improve RRD's ability to produce components with a higher reliability in service and supports efforts to prolong on-wing time and reduce operating costs.

The CPLIFE results will be used in the second quarter of 2003 to compare the predicted life of a combustor z-ring in the BR715 engine with service experience. If successful, this exercise will allow an analysis-based lifing procedure for combustors to be established.

The results of CPLIFE and its exploitation will also be reviewed to identify important issues that have not yet been addressed and implemented in the lifing process. This review will form the basis of a potential Framework 6 proposal for a comprehensive New Lifing Methodology (NLM) programme. The NLM programme, expected to start in 2004, will focus on the incorporation of important phenomena such as multiaxial creep-fatigue and oxidation. Implementation of cycle extrapolation methods for run time reduction will also be addressed in the project.

Further exploitation activities are planned to investigate the potential transfer of the lifing approaches to other nickel base alloys used in disc and blade applications.

Several conference papers discussing major findings from the CPLIFE project have been presented or are in preparation as shown in Section 5.

CNR-TeMPE

CNR-TeMPE proposed an original version of a Continuum Damage Mechanics model for creep strain. This was implemented using CNR's C263 creep data and validated by predicting variable load creep results to a satisfactory accuracy. The model proved to be capable of describing the very different creep behaviour observed at a range of temperatures and stresses.

As a Government owned research organisation, the major exploitation route of the know-how gained by CNR-TeMPE during the project will be via presentation and publication of the results at national and international conferences and in seminars and journals.

Three conference papers and journal articles have already been prepared as listed in Section 5, and two more publications are planned in 2003.

QinetiQ

QinetiQ is a research organisation with a specific capability for lifing hot engine parts for application to aero and industrial gas turbines (IGTs). The results obtained from the project will be of significant benefit to the development of new business in the IGT area. The latter is currently receiving internal investment to facilitate market growth with both Original Equipment Manufacturers (OEMs) and end users of gas turbines. To this end, further collaboration with Alstom plc on combustion materials is planned.

In the course of CPLIFE, QinetiQ developed creep-plastic deformation models and new methods for crack initiation and propagation lifing. The models were extended to include multiaxial loading effects and were applied to the featured specimen and component tests performed in the programme. Additional work is planned on non-linear crack growth modelling to back calculate featured specimen initiation lives. The bulk of this activity will be performed as part of two studentships.

Applications for financial support for further projects building on the results of CPLIFE are expected to be put forward in the EC Framework 6 programme and (with Rolls-Royce) in the Defence and Aerospace Research Partnership (DARP) on Advanced Aero Engine Materials (ADAM).

Within QinetiQ, seminars and meetings are scheduled across the whole organisation to report on research work. The link to the outer world is made via specially appointed Channel Managers who directly address potential new business partners. Additionally, lectures are held at Universities and professional institutions including the Institute of Materials (IoM) and the Institute of Mechanical Engineers (IMechE). Presentations at national and international conferences and papers in journals are also used to communicate with partners in business and academia. Three conference papers have been prepared to date by QinetiQ as shown in Section 5.

EC-JRC-IE

Re-structuring of the European Commission's Joint Research Centres has led a revised definition of the role of EC-JRC-IE. As a result, the Institute's involvement in TMF testing, both for research and commercial purposes, has been scaled down. The only current EC-JRC-IE exploitation activity for its work in CPLIFE is as part of a Framework 5 programme on TMF testing standards.

The experience gained from the CPLIFE tests was used, however, in EC-JRC-IE's contribution to the working document on a thermomechanical fatigue standard under ISO/TC164/SC5/WG9 at the meeting held on 5-6 October 1999. EC-JRC-IE also participated in ASTM Committee 'E08.05.07 Thermomechanical Fatigue', which is developing an parallel standard to ISO, at their meeting on 15-18th November 1999.

FIAT AVIO

Because simulation of the behaviour of structural and mechanical components during their operative life is now the main part of the design process for the aeronautical and transport industries, FIAT AVIO's main objective in CPLIFE was to develop improved virtual tools for more reliable design of components subjected to thermal and mechanical loads.

The starting point for improving component design is an improved thermal prediction capability since all the uncertainties in the thermal model are transferred into the stress and life analyses. FIAT AVIO developed an in-house 2D finite difference code to analyse the combustors tested at Turbomeca that took into account all the heat transfer modes. The code was able to predict the experimental thermal fields well. The next step was the use of a commercial code, P-Thermal, for heat transfer analysis using 3D finite element models. The P-Thermal code has been customised by writing user defined subroutines. This approach based on experience from CPLIFE has subsequently been used in the CLEAN (Component Validator for Environmentally-Friendly Aero Engine) BRITE-EuRam project on validating low emission technologies at running conditions close to those of near term future aircraft engines.

CPLIFE has also presented FIAT AVIO with the opportunity to perform further studies on creep and fatigue. The methods developed will be used for other combustion applications and work is currently under way to include them in FIAT AVIO's design practices.

MTU

To simulate the deformation behaviour under thermal and mechanical loading, an existing model from Wetzel was modified and incorporated in a commercial software code. Additionally, procedures to predict cyclic life under isothermal and anisothermal loading were developed, verified with the experimental CPLIFE data and incorporated in the code. The implementation of these new models in the FEM-code ABAQUS is ongoing and will enable them to be used for component design.

Use of the models as tools for design is expected to increase analysis times for a turbine exhaust casing compared to today's methods. It will, however, increase the life prediction accuracy, leading to much slimmer designs with a reduction in both weight and cost.

The MTU deformation model was reported at the "Fourth international Symposium on Thermomechanical Fatigue" in Dallas on 7/8th November 2001 and was published in the proceedings. Both the deformation and lifing models were discussed at a symposium on "Integral Materials Modelling" on 19th September 2002 in Aachen and will be presented at the "Thermec'2003" conference on July 7-13 in Madrid, Spain.

SENER

The SENER Structure & Mechanisms Department is interested in improving its ability to predict lives for aero engine components based on a better understanding of material behaviour.

During the project, SENER developed and analysed in more detail the Bodner-Partom model to characterise both C263 and Haynes 230. Important gains were made in the knowledge of material behaviour and implementation of material models in ABAQUS for non-linear conditions. The suitability of the Strain Range Partitioning method for life prediction was also studied. The subroutines developed provide a straightforward way to apply this method to other materials.

In the area of efficient finite element methods, several packages were tested. The Cycle Skip Method procedure to save time and computer costs for large non-linear FE analyses is considered worthy of further investigation.

SENER's intention is to introduce the CPLIFE models into their design process (dimensioning, pre-design and final design) to allow time and cost to be saved for new designs. Initial application of the procedures will be for non-critical aeronautical components using existing material databases.

SENER's aim is to continue the work during the 6th Framework, with the intention of introducing software partners in the consortium. The models developed would be implemented by the code developers and would be maintained and updated with particular license agreements for the consortium partners.

SENER has included updated information of the project status in the each Annual Report of the Cluster of the Aeronautic of the Basque Country (Spain) and in the ATECMA (Spanish AECMA), since the project started. The Cluster of the Aeronautic of the Basque Country (Spain) is a non profit making association founded in 1997 by GAMESA AERONAUTICA, ITP and SENER. It has since been joined by a further 15 companies and has the support of the Department of Industry, Commerce and Tourism of the Basque Government.

<u>TURBOMECA</u>

TURBOMECA, like the other gas turbine manufacturers, has to develop a totally new generation of combustors featuring many more zones of high stress concentration (like double walls with multi-hole effusion cooling) than on current designs in order to meet new low NOx emissions requirements. At the same time, due to much stricter new engine certification requirements, the complexity of component life substantiation has increased dramatically. Furthermore, in order to ensure sufficient combustor life, TURBOMECA is obliged to increase the cooling air flow, which acts against the intention of lowering NOx emissions. No methods were available at the start of CPLIFE to accurately predict component life, extrapolate test results precisely to different loading conditions, accelerate engine tests or rank candidate combustor wall materials.

The new rig test developed by TURBOMECA during CPLIFE is capable of recreating precisely the loading conditions of new combustor designs under development. This enables many different versions of cooling features to be tested at a very affordable price compared to full engine tests for the same number of cycles. This will almost eliminate the risk of failing an engine test because of the combustor, and, in the same time, will allow the combustor cooling air flows to be optimised for better overall engine performance and reduced NOx emissions. The rig is already in use to evaluate the feasibility of new combustor materials such as metal matrix composite walls with different thermal barrier coatings.

The material behaviour models and non-linear finite element calculation methods used within CPLIFE are the most advanced currently available, and are also directly applicable to other superalloys. TURBOMECA will therefore implement the new lifing methodologies and strategies developed within this programme and extend them to other components, principally blades and discs, critical rotating parts which are the key for the airworthiness of its helicopter engines.

5. REFERENCES

The current list of journal articles and conference papers resulting from CPLIFE is given below. As mentioned in the partner-specific exploitation plans, further publications and presentations are planned over the next two years.

<u>Alstom Power Sweden</u>

M Hasselqvist, "Differences in Morphology between LCF-Cycled, Crept and Thermally Exposed Haynes 230 and a Discussion about the Implications for Constitutive and Life Modelling for Real Component Conditions", Modelling of Microstructural Evolution in Creep Resistant Materials, Ed. A.Strang & M.McLean, IOM Communications 1999.

M Hasselqvist, "Aspects of Creep-Fatigue in Gas Turbine Hot Parts", Dissertation No. 678, Linköping Studies in Science and Technology, 2001.

M Hasselqvist, “Viscoplastic Modelling for Industrial Gas Turbine (IGT) Application with Emphasis on the Sheet Material Haynes 230”, GT2002-30659, Proceedings of ASME Turbo Expo 2002 3-6 June 2002, Amsterdam, The Netherlands.

Rolls-Royce Deutschland

U Müller, K Höschler, M Gerendas, H-J Bauer, U Schoth, “Mechanical Analysis of an Aero-engine Combustor under Operation Conditions using a Unified Constitutive Material Model for Deformation Simulation”, 9th International Spring Meeting, Société Française de Métallurgie et de Matériaux, 29-31 June 2001, Paris, France.

H Schlums, DS Tchankov, B Meissner, J Villwock, “Life Prediction for High Temperature Low Cycle Fatigue and Thermo-Mechanical Fatigue”, 8th International Fatigue Congress, Stockholm, Sweden 2-7 June 2002, EMAS, UK, Ed. A.F. Blom.

H Schlums, DS Tchankov, K Höschler, U Müller, “Crack Initiation Life Prediction for Notched Specimens based on the Chaboche Deformation Model”, to be submitted to 6th International Conf. on Eng. Structural Integrity Assessment, 7–9 October 2002, Manchester, UK.

CNR-TEMPE

M Maldini, V Lupinc, “Modelling the creep behaviour of Nimonic 263 alloy in a large stress/temperature field”, proc. “Materials for Advanced Power Engineering 2002”, Liège, September 2002, ed.s J. Lecomte-Beckers et al., publ. Forschungszentrum Jülich, Vol. I, (2002) p.409-418.

M Maldini, V Lupinc, E Signorelli, “Descrizione del comportamento a creep di una superlega di nichel in un ampio intervallo di sforzi e temperature”, accepted for presentation and publication at 29°Convegno Nazionale AIM Modena, 13-15 November 2002.

M Maldini, V Lupinc, “Analysis of creep curves of a nickel base superalloy in a wide stress/temperature field”, proposed for publication in Scripta Materialia.

QinetiQ

T Ward, M Henderson, B Vermeulen, “The use of a Chaboche Model in ABAQUS, using Z-aba, to predict the behaviour of a nickel based alloy under thermo-mechanical fatigue”, 2001 ABAQUS Users’ Conference, June 2001, Maastricht, Netherlands.

A Gilmartin, M Henderson, T Ward, B Vermeulen, “Finite Element based Fatigue Crack Growth Simulations in Featured Plate Specimens”, 2002 ABAQUS Users’ Conference, 29-31 May 2002, Newport, Rhode Island, USA.

T Ward, B Vermeulen, “Stress Analysis and Life Prediction of an Aero Engine Combustion Chamber with Angled Effusion Cooling Holes”, 2003 ABAQUS Users’ Conference, in preparation.

MTU

EE Affeldt, J Hammer, L Cerdán de la Cruz, “Modeling of Deformation during TMF-Loading,” Thermomechanical Fatigue Behavior of Materials: 4th Volume, ASTM STP 1428, M. A. MacGaw, S. Kalluir, J. Bressers, and S. D. Peteves, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2002.

6. COLLABORATION SOUGHT

No external collaboration is sought for exploitation of the results of this project.