SYNTHESIS REPORT

FOR PUBLICATION

CONTRACT N° : BREU CT 92 0153

PROJECT N° : BE 5118

TITLE :

DEVELOPMENT OF A NEW ALUMINIUM ALLOY FOR USE AT 150°C

PROJECT COORDINATOR : **AEROSPATIALE** (F)
Centre Commun de Recherches Louis Blériot

PARTNERS :

BRITISH ALUMINIUM Ltd - BANBURY (UK)

BRITISH AEROSPACE **AIRBUS - FILTON** (UK)

DAIMLER BENZ AG - MUNCHEN **(D)**

DAIMLER BENZ AEROSPACE AIRBUS - **BREMEN (D)**

DASSAULT - **SAINT** CLOUD **(F)**

DRA - FARNBOROUGH (UK)

ISTRAM - PATRAS **(GR)**

MIRTEC - VOLOS **(GR)**

ONERA - CHATILLON (F)

PECHINEY - VOREPPE (F)

STARTING DATE : 01.11.1992 DURATION : 48 MONTHS

PROJECT FUNDED BY THE EUROPEAN COMMUNITY UNDER THE BRITE/EURAM
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DATE : 15.01.1997

J. HOGNAT

BRITE
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DEVELOPMENT OF A NEW ALUMINIUM ALLOY FOR USE AT 150°C

G. PONS - Y. BARBAUX

AEROSPATIALE - Centre Commun de Recherches Louis Blériot
BP 76 -92152 SURESNES CEDEX FRANCE

Fax number : (,33)01 469737 30

ABSTRACT

This report presents the work programme and the main results of a cooperative study funded by the CEC under BRITE EURAM programme dedicated to the development, by ingot metallurgy, of a new aluminium alloy for use at 150°C.

The first stage of this research work was focused on the choice of the main Precipitation system in regard to elevated temperature properties. In this objective, tensile and creep properties at 150°C as well as fracture toughness and corrosion behaviour on rolled plates and sheets in 33 different chemical compositions / semi-products, belonging to the main precipitation systems ($\dot{S}$, θ, δ, Ω, T and β), were assessed. The stability for long exposures at 150°C of most of these alloys has been demonstrated on the basis of fine microstructural investigations and mechanical tests. From these results, it has been clearly established that the Al-2Cu-Mg-Ni system, especially the 2650 alloy, was presenting the best compromise in terms of strength, creep resistance and fracture toughness.

In a second step, attempts have been made to optimise the 2 best nominal compositions (2650& 6056), selected from task 1 on the basis of creep results, and the corresponding ageing treatment in regard to the other properties of use (fatigue, fracture toughness & corrosion). The influence of nickel, iron & manganese contents has been particularly studied on the 2650 alloy. The effort was mainly focused on fatigue, toughness and crack propagation properties but limited creep tests were also carried out to make sure that the creep behaviour was not affected by the alloy modifications.

Lastly, the achievement of the original technical and economical objectives has been assessed through a comparison of the properties obtained on the optimised alloys with the target properties defined in the initial work programme. From this comparison, it can be clearly stated that all the original objectives of the programme are met, with the development of 2 alloys which present elevated temperature properties much improved over the best existing alloys, i.e. 2618 and 2219, together with damage tolerance properties comparable to the 2024 alloy, known as a reference in this regard.

These 2 alloys are fabricated with conventional tools and do not contain any expensive constituent. This garantees that the cost objective is also attained. Besides, the 2 alloys developed do not contain any toxic element, such as nickel, which is present in the 2618 alloy. This is a very positive argument in regard to environment and recyclability.

Two patents have been applied by PECHINEY and AEROSPATIALE as a result of this R & D project: one on the composition of the 2650 alloy and one on the application of this alloy to structural components of aircrafts.

Keywords : Aluminium alloys - Rolled products - Development - Temperature - Properties

1 - THE CONSORTIUM

1.1 - PARTNER ORGANISATIONS

Company	Adress	Contact person	Fax number
AEROSPATIALE DCR/M CCR Louis Blériot	4 bis rue du Val d'or 92150 SURESNES FRANCE	Y. Barbaux G. Pons	(33) 01 46973730
BAe AIRBUS Ltd Materials & Processes Technical centre (DI)	P.O. BOX 77 FILTON BS99 7AR BRISTOL ENGLAND	M. O'Neill	(44) 1179365903
BA ALUMINIUM Alcan Speciality & Aerospace Ltd	P.O. BOX 383 KITTS GREEN B3390R BIRMINGHAM ENGLAND	M. Reynolds A. Morris	(44) 1295 2742_16
DASSAULT AVIATION	78 quai Marcel Dassault 92214 ST. CLOUD FRANCE	B. Day	(33) 0147115585
DAIMLER BENZ	Postfach 801220 OTTOBRUNN 08000 MÜNCHEN 80 GERMANY	E. Reese	(49) 8960725408
DAIMLER BENZ AEROSPACE AIRBUS	Hünefeldstrabe 1-5 Postfach 107845 2800 BREMEN 1 GERMANY	W. Entelmann	(49) 4215384180
DRA AV[ATION AND MILITARY DIVISION Materials and Structures Department	FARNBOROUGH, H-ANTS GU146TD'FARNBOROUGH ENGLAND	S.Flitcroft W. Mitten	(44) 1252394135
ISTRAM Institute of Structures & Advanced Materials	PATRON PYRGOU 16 26500 PATRAS GREECE	S. Pantelakis	(30) 61520881
MIRTEC physical Metallurgy	A industrial area of Volos 38500 VOLOS GREECE	Mrs. Papadimitriou	(30) 42 I 95 364
ONERA Division OM	29 avenue de la Division Leclerc 92320 CHATILLON FRANCE	G. Lapasset H. Octor	(33) 01 '467341 42
PECHINEY Centre de Recherches	CRV SA - BP 24 38340 VOREPPE FRANCE	r) Bechet	(33) 01 7057 so 99

1.2 - CONSORTIUM 1) ESCRII'TION

The following table sum marises the contribution of the different par triers for the different tasks.

Partner (n")	Business Profiles	Main Contribution (task numbers)
Aerospatiale (1)	Aircraft Manufacturer	Project Management - Definition of target - Evaluation - Management {1.1 ,1.3,2.2,3,4)
BAe Airbus Ltd (2)	Aircraft Manufacture	Definition of target Evaluation (1. 1,1.3,2.2,3)
Daimler Benz Aerospace Airbus (3)	Aircraft Manufacturer	Definition of target - Evaluation(1.1, 1.3,2.2,3)
D. R. A.(4)	Research Institute	Management of alloy development - Fabrication of experimental alloys (1.1,1.2, 1.3,2.2,2.3,3)
ONERA (5)	Research institute	Microstructural investigations (1. 1,1.3,2.2,2.3,3)
ISTRAM (6)	Research institute	Understanding of behaviour (1.1,1.3,2.2,2.3,3)
B.A. Aluminium (7)	Aluminium alloys Manufacturer	Development of alloys (1.1, 1.2,2.1,2.3,3)
PECHINEY (8)	Aluminium alloys Manufacturer	Development of alloys (1.1,1.2,2. 1,2.3,3)
Dassault Aviation (9)	Aircraft Manufacturer	Associate partner of Aerospatiale (1. 1, 1.3,2.2,3)
Daimler Benz (10)	Automotive Manufacturer	Associate partner of Daimler Benz Aerospace Airbus (1.3,2.2,3)
MIRTEC(11)	Industrial R & D	Associate partner of Is tram (,1. 1,1.3,2.2,2.3,3)

2 - INTRODUCTION

This report presents the work programme and the results of a cooperative study between AEROSPATIALE (F), BRITISH ALUMINIUM Ltd (UK), BRITISH AEROSPACE AIRBUS Ltd (UK), DAIMLER BENZ AG (D), DAIMLER BENZ AEROSPACE AIRBUS (D), DASSAULT (F), DRA (UK), ISTRAM (GR), MIRTEC (GR), CNERA (F) and PECHINEY (F), supported by the CEC under BRITE EURAM contract BRE2 CT9201 53, which aims at developing a new creep resistant aluminium alloy for use in the range 100°- 200°C. The new alloy should be available at a low cost i.e. being fabricated by ingot metallurgy, easy to transform with conventional tools and able to hold very long time exposures without a significant loss of properties.
The driving force for such a development work was the preparation, of a new supersonic aircraft project. Nevertheless, potential applications on subsonic aircrafts and helicopters had also been identified and benefits in terms of cost and weight savings had been estimated.

Developed at the beginning for the Concorde programme, the 2618 alloy is widely used up to now for elevated temperature applications in many industrial sectors, mainly when high damage tolerance properties are not required.

In Europe, during the seventies, studies were undertaken to improve the fracture toughness of 2618 alloy. This led to the development of 2650 alloys. These alloys, with chemical composition close to that of 2618, present improved fracture toughness properties; unfortunately no long term creep properties are available from them, since their development was stopped when the project of an improved Concorde was abandoned. More recently, studies were conducted on 8090 aluminium-lithium alloy, interesting for its low density and presenting a relative good creep behaviour. However, this alloy is suspected for having not a stable microstructure in the temperature regime concerned which results in a decrease of its fracture toughness after short exposures at elevated temperature.

In Australia, Pr. Polmear has developed, for forging applications, an alloy derived from 2219 with silver additions, presented as very creep resistant.

In the United States, Reynolds company which already developed 2048 alloy, for a supersonic project in the sixties, is currently developing an aluminium-lithium alloy called RX 818 which would be stable at elevated temperature; while Alcoa developed the 2519 alloy, presented as a very creep resistant alloy.

Unfortunately, for these two last products, which are in a development phase, it is very difficult to get information corresponding to our objectives, and impossible to get material for evaluation without being linked with a commercial and confidential contract.

It was thus decided to base the programme on a further optimisation of the already investigated systems, taking into account the specific requirements for airframe structure applications.

3 - WORK PROGRAMME

The original development work programme was divided in three major phases:

- task 1 - Choice of the main precipitation system,
- task 2 - Optimisation of composition and processing,
- task 3 - Evaluation of the project.

- In task l, alloys Compositions" from the best systems selected in a litterature survey were to be compared on the basis of the evaluation of elevated temperature mechanical properties (mainly creep & thermal stability) in relationship with microstructural features (grain size, morphology & texture, precipitation, intermetallic compound).

- Task 2 was dedicated to the optimisation of the chemical composition and the associated process of the two nominal compositions, selected from task 1 on the basis of creep resistance, in regard to the other proper-lies of use namely fatigue, fracture toughness and crack propagation, checking that the creep behaviour was not affected by alloy modifications.

- Lastly, the objective of task 3 was to demonstrate that the achievement of the original technical and economical objectives has been assessed, through a comparison of the properties obtained on the alloys tested in task 2 with the target properties defined in the work programme and with the results obtained on the existing alloys established in the synthesis of subtask 1.1.

4- MAIN ACHIEVEMENTS

4.1 - CHOICE OF THE MAIN PRECIPITATION SYSTEM ,

The first and main factor that influences the elevated temperature behaviour, especially creep resistance, of aluminium alloys is the main precipitation system. Thus an extensive investigation was undertaken by all the.partners to collect information from existing aluminium alloys based on S, θ, δ, Ω, T and β precipitation. Data were collected on the following alloys:

- 2000 series
  - -Al-2Cu-Mg :2618A& 2650
  - -Al-4Cu-Mg :2014-2024-2124-2048
  - -A1-6Cu-Mn-Mg:2219 -2419 -X3058

- 6000 series
  - -Al-Mg-Si-Cu :6013 & 6061

- 8000 series
  - -Al-Li-Cu-Mg :8090

From this work it appears that the Al-2Cu-Mg-Ni system presents a very good overall creep behaviour but, on the basis of Larson Miller extrapolation, none of these alloys does meet the creep elongation requirement which is less than 0.1% after 60 000 hours at 130°C under 150 MPa. Among them, 2650 alloy with a lower Fe and Ni contents than 2618A, presents a much better fracture toughness than the Concorde alloy and meets the objective requirements

Besides, 6013 (Al-Si-Mg-Cu) and 8090 (Al-Li-Cu-Mg) alloys, with a, lower density, meet the fracture toughness requirements and present a very good creep behaviour in the primary and secondary stages. However, these' two alloys exhibit a very small tertiary creep stage, with a very small creep failure elongation (below 1%) which indicates a very rapid growth of the creep damage.

Following the conclusions of this work, four precipitation systems were selected, resulting in a total of 33 products corresponding to 23 different chemical compositions. The alloys production was shared between the three elaborators involved in the programme (DRA, BRITISH ALUMINIUM Ltd and PECHINEY) according to the table 1.

PECHINEY	BRITISH ALUMINIUM Ltd	DRA
4 alloys 2 forms (sheet & plate) (1)	5 alloys plates	20 alloys sheet
2650 + Ag 2650 + Zr X 2525 X 2525 + Zr	X 2525 (2)(3) X 2525 + Ge(3) 8090 (3) 6013 (4) MD 345	2650 (9 compos.) X2525 (4 compos.) 2024 (4 compos.) Al-Li (3 compos.)

Table 1 - **Alloys selection to be produced for task 1**

(1) Target of 2 different microstructures
(2) X 2525 corresponds to X3058 / 2001 compositions
(3) Non recrystallised structure
(4) Recrystallised and non recrystallised

- At BRITISH ALUMINIUM Ltd, the 8090, X2525 (Al-5.5Cu-0.5Mn-0.35Mg) with and without Germanium and MD 345 (Al-2.6Cu-1.6Li-0.5Mg-0.3Ag) alloys were cast without any problem (only the Copper level was a little bit low on the X2525 with Ge). On the opposite, the casting of 6013 was very difficult and the ingot presented some cracks. The five compositions were homogenised and hot rolled to 14 mm plates and then salt bath solution heat treated. On 6013 alloy, BRITISH ALUMINIUM Ltd could not obtain products in the 2 foreseen microstructure (recrystallised/non recrystallised) but got plates presenting an heterogeneity of microstructure in the thickness (recrystallised near the surface & unrecrystallised at mid thickness).

- At **PECHINEY**, 4 alloys identified as 2650 + Zr, 2650 + Ag, X2525 and X2525 + Zr were cast with a cross section of 380 x 120 mm at the foundry of the Centre de Recherches de Voreppe. ALPUR degassing of the melt was performed to assure good quality of the castings. There was no particular difficulty noticed for the casting of the 4 alloys, and the elaboration of the material was successful at the first attempt. Ultrasonic non-destructive control was performed and showed no defects. After homogenising at 520 °C, hot rolling was done to produce plates in two thicknesses : 14 mm and 4 mm. The last transformation was done by cold rolling the 4 mm thick sheets down to the final thickness of 1.6 mm. Because of the limitations of its laboratory equipments, the maximum width of the products from CRV were 70 mm for the plates and 170 to 200 mm for the sheets. The only difficulty encountered by PECHINEY concerned the solution heat treatment (SHT) of X2525.

- At **DRA**, the 20 alloys which were planned from the 2650, X 2525, 2024, 8090 and Al-Cu-Li-Mg-Ag systems were cast and processed to sheets 1.6 mm thickness. Concerning the heat treatment conditions, because of the large number of alloys, it was impossible to make a study of optimization of the heat treatment conditions for each alloy. Thus it was decided that the nominal conditions for the basis alloy will be selected (for instance the heat treatment of 2618 will be used for 2650 and its variants). It was also decided that the amount of stretching after quench would be of 2% for all alloys except the Al-Li alloys.

The 14 mm plates and 1.6 mm sheets were then dispatched to the different partners to carry out the following investigations:

- Thermal stability at 150°C after 1000 and 4000 hours exposure
- Tensile tests at 20 and 150°C on the as received material
- Tensile tests at 20 and 150°C after 1000 and 4000 hours conditioning at 150°C
- Creep tests at 150°C under 250 MPa
- Fracture toughness tests at 20°C
- Corrosion

The thermal **stability** of the alloys was studied by ONERA. The evolution of the microstructure of these alloys was assessed' through Hardness measurements. After a 4000 hours exposure, most of the 2650 type alloys exhibit hardness 10S ses inferior to 10%. Only the 2650 + Ag alloys from PECHINEY and DRA, which are very hard in the as received condition, show an important loss (resp. 20 and 1570). The X2525 type alloys seem to be much more thermally stable with hardness losses in the range 6 - 12%, while the Al-Cu-Li alloys (Mod 049, RX218, MD345) all exhibit a strong hardness increase after a 1000 hours exposure. This behaviour is even more pronounced *in the case of the* 8090 alloy.
Among the 2024 alloys familly, the basis alloys 2048 and 2124 are very stable, while those with Zr or Ag additions exhibit a loss between 7 and 10%.
The. 6013 alloy is proved to be quite thermally stable (loss= 570).

Tensi **le** tests were performed by BAe, DASSAULT and DAIMLER BENZ AEROSPACE AIRB US. The comparison of tensile results, in the as received condition and after 1000 and 4000 hours soak at 150°C, showed the following u-ends:

● 'C)n the 2650 alloys, no effect of the thermal ageing was evident ed at room temperature while at 150°C, most of these alloys exhibit strength losses (Y.T. S. and U. T-S.) close to 10%, except the 2650 + Ag from PECHINEY and the DRA alloy G 78 containing 0.5% Si and 0.5% Ag, which show higher losses (>20 %).

• In general, X2525 alloys exhibit lower strength losses at 150°C than 2650 alloys, in the range 6- 19% for the Y.T.S. and 1- 12% for the U.T.S. Furthermore, the two alloys manufactured by BRITISH ALUMINIUM Ltd seem to be very thermally stable.

•Aluminium lithium family (8090, MD 345, Mod 049, RX 218) exhibit, both at room temperature and 150°C, a significant improvement of tensile properties (from ≈ 10 to 40%) after 1000 hours soaking, while after 4000 hours soaking and when tested at 150°C, these alloys exhibit a drop of properties, leading to partially recover their initial level in as received condition. This behaviour is probably due to the fact that they are initially underaged and that they undergo a *second ageing* step *during* the thermal exposure at 150°C.

•2124 type alloys are not thermally stable and exhibit strength losses between 15 and 25% while the 6013 appears to be much more thermally stable (strength loss ≈ 10%).

Creep tests were shared between DRA. ONERA and ISTRAM. Half tests were carried out up to failure whereas the half remaining were stopped at 1000 hours if no failure occurred before. Concerning results obtained on sheet-s, the main conclusions can be summarized as follows:

• The best creep behaviour is encountered on the 2650 alloys (Figure 1). Although the creep life strongly depends on the chemical composition, it has been clearly demonstrated that the increase of copper (alloy G89) and magnesium (alloy G88) contents as well as the addition of zirconium (alloy G74) were detrimental to the creep behaviour, while increasing either the silver (alloy G76) or the silicon (alloy G73) contents led to a significant improvement of the creep resistance. It has also been noticed that when mixed in same amonts (alloy G78), these two elements do not procure any additive effect.

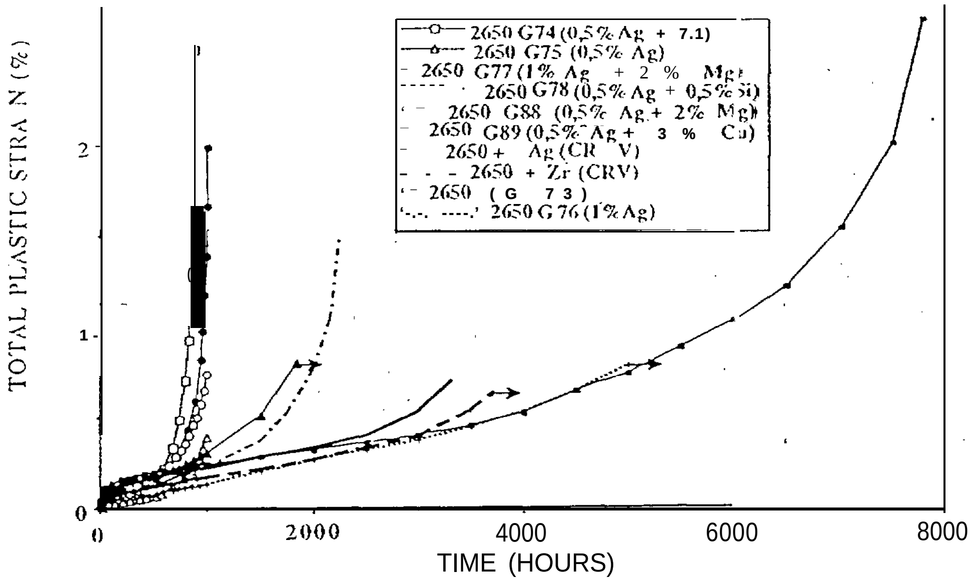

Fig 1 - Creep **results for 2650 sheet alloys**

• The X2525 alloys exhibit a creep behaviour depending both on the process and the chemical composition. Alloys produced by PECHINEY appear more creep resistant than those produced by DRA. Besides, the addition of zirconium seems to have a beneficial effect on the creep life that should be carefully studied. However, the X2525 has a higher density than 2650 which is not balanced by any benefit in creep behaviour.

• The aluminium lithium family (8090 - RX 218- Mod 049) exhibit a poor creep behaviour, mainly the 8090 alloy which fails prematurely. In fact, for these alloys, test conditions were too severe with stress levels close to the yield strength and this explains their poor creep behaviour.

• Among the 2124 family, the 2048 alloy presents a poor creep behaviour both measured by DRA and ISTRAM. On the other hand, creep results obtained on the 2124 series are strongly different depending on the laboratory- Plastic strains measured by DRA are similar to those observed on the 2048 alloy and four time greater thin those measured by ISTRAM. In fact, as no difference of creep results was observed in the other alloy systems, it is thought that creep methodologies must not be questionned and that this effect is due to heat tratment conditions. As a matter of fact, the ageing was directly performed by each partner concerned before testing and it is wellknown that a slight variation in the heat tratment conditions may explain this difference.

• Creep results obtained on plates are better than those obtained on sheets with lower plastic swains measured after 1000 hours testing. Unfortunately most of the tests were stopped at 1000 hours. Only some tests were pursued at DRA on aluminium lithium (8090 & MD345) from BRITISH ALUMINIUM LTD and **X2525** and .X2525 + Zr from PECHINEY, indicating that a ranking of alloys based on plastic strains after IO(M) hours testing can be totally different from a ranking based on the creep li I-c.

Concerning the **corrosion behaviour**, 2650 alloys are more or less sensitive to stress corrosion cracking and to exfoliation depending on their chemical composition and sensitive to intergranular corrosion. X2525 are no sensitive to stress corrosion cracking and exfoliation and more or less sensitive to intergranular corrosion depending on an once producer, chemical composition and semi-product. Aluminium lithium present both a good resistance to stress corrosion cracking and intergranular corrosion (except the 8090 from DRA), and a medium sensitivity to exfoliation. 2124 and 6013 alloys are insensitive to stress corrosion cracking and exfoliation and sensitive to intergranular corrosion.

Results of **fracture toughness** tests, only performed on plates, exhibit high values of K1c, probably no valid because of low specimen thicknesses but also strong differences between values measured by the two laboratories in charge of these tests (DA1 MLER BENZ AEROSPACE AIRBUS and ISTRAM).

Following **microstructural investigations on** the **2650** type alloys tested in task 1. ONERA proposed an interesting interpretation of the relationship between microstructure and creep properties as a function of chemical composition, more particularly in regard to Ag and Si contents.

The main points of this study are:

- The confirmation of the presence of an unknown phase, different from S', in the Ag containing alloys. This phase had previously been reported by J.T. VIETZ and Al. (then called T' as it appears to be a precursor for T phase), and more recently by H. D. CHOPRA and Al.(then called X phase),
- The creep behaviour seems to be more dependant upon the fineness of the precipitation than on its nature (X or S'),
- Considering their microstructure, it appears that the precipitation heat treatment of the medium Ag/medium Si alloys was not optimised. Improvements of the creep behaviour may certainly be obtained by modification of the thermomechanical treatment of these alloys.

4.2 - OPT1M1SATION OF COMPOS1TION AND PROCESSING

The finals ynthesis of task 1 showed that 2650 and X2525 were the best alloys as far as creep and thermal stability were concerned- Particularly, a significant improvement of the creep behaviour was obtained on the 2650 alloy by an optimisation of the chemical composition. The most favorable effect was found either by increasing the silicon content to 0.5% without the addition of silver or by increasing the silver content to 1 % in conjunction with a low silicon content. In regard to cost, density and environment (recycling considerations, it appeared preferable **to** promote, for task 2, alloys containing silicon rather than silver.

Three variants of the chemical composition were chosen for the 2650 as indicated in the table 2 here below:

	Cu	Mg	Mn	Si	Fe	Ni	Ti
2650 base	2.7	1.65	0.35	0.4	0.22	0.2	0.1
Variant 1	2.7	1.65	0.35	0.4	0.1	-	0.1
Variant 2	2.7	1.65	0.6	0.5	0.2	0.2	0.1

Table 2 - 2650 Chemical Compositions Selected for Task 2

Although not studied in task 1, it was decided to add the 6056 alloy to the previous alloys. As a matter of fact, this alloy derived from the 6013 alloy has shown an interesting potential without any optimisation, during preliminary creep tests performed at AEROSPATIALE. Furthermore, the 6056 is weldable, presents a lower density than the 2650 and may be used as well for subsonic as for supersonic applications.

Material in plate form was to be produced by BRITISH ALUMINIUM Ltd while both plate and, sheet was to be produced by PECHINEY. The variations in fabrication practice (homogenisation temperature, solution heat treatment practice) was confined to the. material produced by PECHINEY. In total 14 different material configurations were produced for evaluation in task 2, according to the table 3 here below:

	PECHINEY		BRITISH ALUMINIUM Ltd
	Plates	Sheets	Plates
2650 base	2	4	1
2650 Variant 1	I --	1	1
2650 Variant 2	1	1	1
6056			1

Table 3 - Alloys **to** be produced **for Task 2**

• **At BRITISH ALUMINIUM Ltd**, DC cast ingots measuring 170 mm thick by **450** mm wide were cast of sufficient length to produce two 1 metre long ingot for hot rolling.
The 2650 compositions were homogenised by ramping at 50°C/hour to 500°C and then at 5°C/hour from 500°C to 520°C before soaking at 520°C for 24 hours. The 6056 was similary ramped to 500°C, then at 10°C/hour to 530°C and soaked at that temperature for 14 hours.
All the ingots were scalped to 150 mm thick after homogenizing for hot rolling up to 14 mm.
After hvo preheats between 8 and 16 hours at 500°C and 480°C, the plates were edge trimmed to approximately 400 mm prior to heat treament.
The 2650 plates were solution heat treated for 1 hour at 530°C, cold water quenched, and stretched 2%. The 6056 plates were solution heat treated for 2 hours at 550°C, cold water quenched "and stretched 2%. Following stretching, the 2650 plates *were* aged at 190°C for 19 hours while the 6056 plates were, aged at 175°C for 8 hours.
The grain structure of the finally heat treated plate was examined.. All the variants of 2650 had the same grain structure which is fine and partially recrystallised. The 6056 plate grain structure was coarser and largely unrecrystallised.

• **At PECHINEY,** ingot measuring 120 mm thick by 380 mm wide were produced from 125 Kg melts. The base alloy was homogenised at either 520°C (A1) or 490°C (A2). All the remaining material was homogenised at 520°C. The soak time was the same as that used by *BRITISH ALUMINIUM LTD* i.e. 24 hours.
14 mm plates and 1.6 mm sheets were produced. "1-hc sheet.s production involved hot rolling to 4 mm [hen cold rolling to the final gauge. The plates were solution heat treated in air using the same practice as employed by BRITISH ALU MI NIUM Ltd i.e. I hour at 530°C, while two solution heat treatment practices were used for sheets with the base alloy composition. Sheets were solution heat treated at 530°C for 40 minutes in either an air furnace or in a salt bath. The identifications given to the various sheets are shown *in table 4*.
All plates and sheets were stretched 1.4% and aged for 19 hours at 190°C.
An examination of the grain size showed that the sheet solution heat treated in the salt bath had a grain size of 25 μm while that heat treated in air had a grain size of 50 μm.

Sheet identification	Alloy variant	Homogenisation temperature and S. H.'". medium
A1-1	2650 base	520°C - Air
A1-2	2650 base	520°C - Salt
A2-1	2650 base	490°C - Air
A2-2	2650 base	490°C - salt
B1-1	2650 variant 1	520°C - Air
C1-1	2650 variant 2	520°C - Air

Table 4 - Identification of the Sheets produced by PECHINEY

In order to assess the different alloys, a work programme based on mechanical testing in conjunction with microstructural investigations was defined. The effort was mainly focused on tensile, fatigue, toughness and crack propagation properties, but limited creep tests were also carried out to make sure that the creep behaviour was not affected by the alloy modifications.

Tensile tests performed by BAe indicated that on sheets, properties (Y.T.S. and U. T. S.) are similar for each condition (20 an'd 150°C) on the 6 alloys. However, it can be observed that the drop of properties due to temperature is higher than in task 1. When compared to the G 73 alloy of task 1, which is the best creep resistant alloy, the Y.T.S. is reduced from 22 to 26 % instead of 10% (Figure 2). On plates, the same trend is observed on 2650 alloys but the Y.T.S. is only reduced from 13 to 19% when the temperature goes from 20 to 150°C. Besides, no significant difference was found between the two producers (BRITISH ALUMINIUM Ltd and PECHINEY). The 6056 exhibits 10 wer properties than the 2650 but the drop of. properties is smaller and limited to 12%.

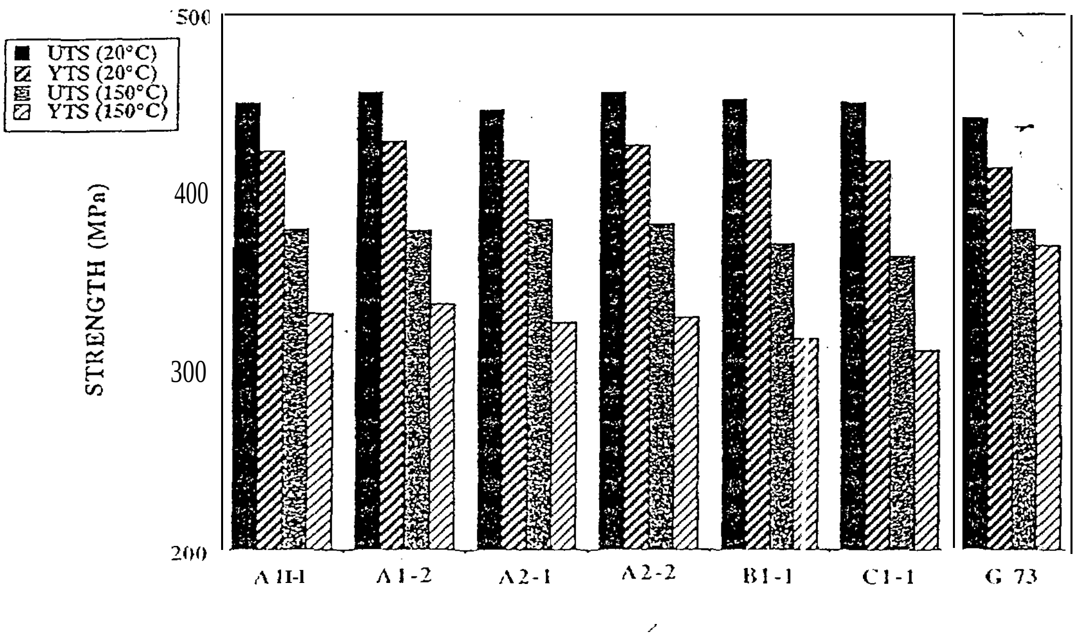

Figure 2 - Tensile Results on 2650 Sheet Alloys

Fatigue tests on plate alloys from BRITISH ALUMINIUM Ltd and PECHINEY were also conducted by BAe. Specimens used were, notched specimens (K_t=2.68), extracted following the long direction. Tests were performed at 20 and 150°C, with a R ratio=0. 1. From the results it can be drawn that all the 2650 variants have the same behaviour and the influence of temperature is almost negligible, at least, for the higher stresses. As far as ***the*** 6056 is concerned, the same conclusions hold. When comparing the 2650 to the 6056 under the same conditions it appears that the 6056 has a lower fatigue behaviour which can be related to plasticity.
On sheets tests were performed by MIRTEC at 20°C and by DAIMLER BENZ AEROSPACE AIRBUS at 150°C on notched specimens (K_t=2.5). At 20°C, no difference was found between the different alloys and the fatigue limit at 107 cycles may be estimated at about 130 MPa. At 150°C, no difference also was found between the different alloys, but due to the effect of temperature the fatigue limit was lowered from 130 to 100 MPa. However, as each partner was in charge of machining its own specimens, it is not sure that 'his effect is only related to temperature. In connection with this, the two partners were asked to check where initiation takes place.

Toughness tests (R curves) were conducted by AEROSPATIALE on plate alloys from BRITISH ALUMINIUM Ltd. Specimens used were CCT specimens: 1000 x 400 x 6 mm, extracted following the long direction in the middle of plates (thickness=14 mm). Tests were performed according to ASTM E 561-93 using simple compliance "method. Crack opening measurements were made by laser.

The main results can be summarised as follows:

- All the alloys fulfill the *minimun* toughness requirements (equivalent to 2024 T3).

- Due to invalidity of some tests it was not possible to rank the alloys based on Kc. however on the basis of load at fracture the ranking is:

  1) 6056
  2) 2650 (High Mn)
  3) 2650 (Base)
  4) 2650 (0% Ni)

- Among the 2650 alloys, the high Mn content exhibits a better resistance to ductile tearing although all the alloys have the same mechanical properties (mainly ductility).

Toughness tests were also performed by DAS'SAULT on sheet alloys from PECHINEY. Specimens used were CCT specimens: 600 x 200 x 1-6 mm extracted from the long direction. Crock measurements were made using potential drop technique.
Results stun to indicate that although all alloys reached the target, alloys B I-1 (0% Ni) and C I-1 (high Mn) exhibit the best toughness (Kc >-125 MPa$\sqrt{m}$).

Crack propagation tests were shared between the partners in volved according the table 5 here below:

	PLATES		SHEETS	
	R 0.1	R 0.5	R 0.1	R 0.5
L-T / R.T.	DBA Airbus	Aerospatiale	Daimler Benz	DASSAULT
T-L / R.T.	DBA Airbus	Aerospatiale		
L-T / 150°C	DBA Airbus		Daimler Benz	

Table 5 - Crack propagation test conditions

On plate alloys, produced both by BRITISH ALUMINIUM Ltd and PECHINEY, specimens used were CT specimens 50 mm wide and 12 mm thick, extracted in the middle of the plates, following the long and transverse direction. Tests were performed at a frequency of 20 Hz. Results seem to indicate that the influence of the direction and the temperature (mainly for the high crack growth rates) is more significant than the influence of the chemical composition (for the 2650) and the producer (for the same product).

On sheet alloys, only produced by PECHINEY, specimens used were CCT specimens between 100 and 160 mm wide extracted from the long direction. Results show no influence of the temperature and the chemical composition.

Creep tests were performed by: AEROSPATIALE, DRA, ISTRAM and ONERA with several conditions of stress and temperature:

ISTRAM conducted creep tests in accelerated conditions (250 MPa - 175°C), on 2650 and 6056 plates produced by BRITISH ALUMINIUM Ltd and 2650 plates and sheets produced by PECHINEY, corresponding to 14 different conditions, with two tests per condition.
The main results can be summarised in the table 6 here below-:

			Creep life	Minimun creep strain rate
PECHINEY	2650 Sheets	Best	A1-2	A1-2
		Worst	C1-1	C1-1
	2650 Plates	Best	C1	C1
		Worst	A2	B1
BRITISH ALUMINIUM Ltd	2650 and 6056 Plates	Best	C1 (2007)	C1 (2007)
		Worst	6056, (2016)	6056 (2016)

Table 6 - ISTRAM Creep Results

As far as creep life and minimun creep rate are concerned, it can be noticed that alloy C1 (high Mn) gave the best results both on BRITISH ALUMINIUM Ltd and PECHINEY plates and the worst on sheets. Besides, no particular difference was found on creep lives between plates and sheets.

Although this work was not initially planned in the programme 0- task 2, AEROSPATIALE has performed creep tests on 2650 plates, produced by PECHINEY, in the same condition as ISTRAM (250 MPa - 175°C). From the results analysis, it seemed that alloy A1 was the best as far as creep life and minimum strain rate were concerned, while alloy B1 was the worst.

DRA carried out creep tests in accelerated conditions (180 MPa - 175°C), on 2650 and 6056 plates produced by BRITISH ALUMINIUM Ltd and 2650 plates and sheets produced by PECHINEY, corresponding to 14 different conditions, with one test per condition. The main results can be summarised as follows:

- On sheets, after more than 6000 hours testing, alloy B 1-1 appears to be the best, both in terms of creep life and minimum creep rate.
- On plates, the 6056 alloy exhibits the lowest creep behaviour while among 2650 alloys, the best creep behaviour is observed on alloys without Ni (2012 from BRITISH ALUMINIUM Ltd) and with high Mn content (C1 from PECHINEY and 2005 from BRITISH ALUMINIUM Ltd).

DRA also conducted some tests at 150°C with two levels of stress: 250 and 190 MPa on plate alloys A1 and B 1 from PECHINEY and C1 (2005) and 6056 (2016) from BRITISH ALUMINIUM Ltd. At 250 MPa, after more than 2000 hours testing, the best creep behaviour is observed on the alloy A 1 and the worst on the 6056 alloy which has already failed. At 190 MPa, considering the low creep strain (< 0.170) all the creep curves fall within 0.02 % scatterband. Note after 4000 hours testing that the C 1 (2005) curve runs along the lower part of the scatterband.

Sheet alloys A2-1 and B 1-1 from PECHINEY were only tested at 190 MPa. After 5600 hours of test alloy A2- 1 exhibits the best behaviour.
It can also be noticed that tests performed at DRA under the same conditions of stress and temperature, both on plates and sheets, evidenced an effect of thickness. The best results were obtained on plates.

ONERA performed creep tests on sheet alloys from PECHINEY in accelerated conditions (250 MPa - 150°C). Except the alloy Al-1 which failed prematurely, all the other alloys exhibit the same trend. Besides, as the minimum creep rate is similar for the 6 alloys, something wrong during testing may be suspected to explain the poor creep life of alloy A 1-1. Furthermore, as far as creep life is concerned, it can be noticed that the best alloys of task 2 are two times lower than the best of task 1(alloy G73 from DRA and alloy 2650+ Zr from PECHINEY).

ONERA also conducted **microstructural investigations** on the **2650** plate alloys from PECHINEY. The main results can be summarised as follows:

- Coarse phases:
  - Mg_2Si and α-phase Al-Mn-Fe-Si on all alloys and also:
  - Al_9FeNi, Al-Cu-Ni and Al-Cu-Fe on alloy A1
  - Al-Cu-Fe on alloy B 1
  - Al-Cu-Ni on alloy C1
  - Al-Cu-Ni and Al-Cu-Fe on alloy A 2
- Dispersoïds:
  - Mainly α-phase Al-Mn-Fe-Si in all the plates
- Hardening phase:
  - S' with in the base alloy (A) similar precipitation within G73

From tests performed in Task 2, the following conclusions can be drawn:

The 6056 alloy exhibits a very good fracture toughness, higher than the 2650 alloys. Fatigue and crack propagation properties are similar on the two alloys while the creep behaviour of the 6056 is lower than the 2650 alloys, mainly when the creep conditions are very severe.

Concerning the 2650 alloys, as no significant difference was found, on mechanical properties (tensile, creep, fatigue, toughness) between the three variants and their associated process, it appeared preferable to promote, for further development, and from an industrial viewpoint (recycling), the alloy nickel free.

5 - EXPLOITATION OF RESULTS

5.1 At the alloy producers

The best established aerospace high temperature aluminium alloy is today 2618, which was originally developed for engine pistons but is mainly known as the Concorde alloy. Both BRITISH ALUMINIUM Ltd and PECHINEY RHENALU had a considerable involvement in the production of this alloy. Apart from use on Concorde this alloy has found applications on other air-crafts like Airbus in part hot areas as the de-icing equipment on the wings. It has also been used for rotor and blades in vacuum pumps, ground turbines and as tooling plate in the U. S. A., i.e. moulds made for curing plastics and rubber articles. BRITISH ALUMINIUM Ltd has become a major player in the tooling plate market and has developed 7000 series alloys for these applications. The significantly better alloys developed in this project will be exploited for such uses.
For both companies, that are ideally equipped to exploit any of the new high temperature aluminium alloys developed in the present programme, the exploitation of a high temperature alloy enter the industrial policy of development of high technology products. Moreover, within the two companies there are capabilities to produce high strength extrusions that will be required in the airframe of the future supersonic aircraft.
Competition for the different markets between BRITISH ALUMINIUM Ltd and PECHINEY would generally be on price and delivery, but it should be pointed out that co-operation between the companies has already taken place in many occasions in the past, like during the development of 7010 and 8090 alloys. It will be the mutual interest of the two companies to work together to get specifications written and, for example, gain MIL HDBK 5 entries which could achieve potentially wider market penetration, especially in the U.S.A.

5.2 At the end-users

The total market foreseen today for the future supersonic civil transport aircraft varies from 350 to 1000 machines, according to the different hypothesises concerning the fare increase for such an aircraft, which will have to be fabricated between 2005 and 2015- It is estimated that the supersonic will require about 200 tonnes bought weight of aluminium product per aircraft. This leads to a potential market of 70,000 to 200,000 tonnes over a period of about ten years. However, the development of this new supersonic aircraft has not been decided yet, and it is foreseen that new materials, which have to be selected in 1999, will only be need for the first production in 2003. This leaves about 6 years for verifying at the industrial scale the performance of the developed alloys and for making all the necessary tests to produce the design allowable.
Besides, the new alloys will also be used in replacement of 2618 and 2219 alloys on subsonic aircraft, helicopter and space vehicles, for such applications as air intakes, fuselage parts in the gas ejection zone, structural parts near the engines. The overall market for these applications represents a smaller market, estimated at about 500 tonnes per year, but it corresponds to shorter time applications. However, about half of these applications correspond to forged components: the adaptation of the developed alloys to this type of semi-product will thus require further development work.

5.3 Patents and publications

In the course of this project, in order to facilitate and support the further industrial and commercial exploitation of the developed alloys, two patents have been applied on 28th of July 1995:

- The first one by PECHINEY, concerning the modification of the 2650 alloy composition, registered under the n°: 9509443,

- The second one by AEROSPATIALE, on the application of such alloy to structural components of aircrafts, registered under the no: 9509246.

Besides, two papers were presented at International Conferences :

- New Creep Resistant. Aluminium Alloys For The Future Supersonic Civil Transport Aircraft, Y. BARBAUX and Al., 4 th European Conference on Advanced Materials and Processes, Padua 25-2819f 1995.

- The Long Term Elevated Temperature Behaviour of Materia 1s: A Key Issue for the Next SST, Y. BARBAUX and AL, ICAS 96, p. 937.

5.4 Further R & D actions needed before commercial exploitation

Some actions will be achieved in a very short term to facilitate the promotion of the new alloys :

- A draft of E.N. specification shall be submitted by AEROSPATIALE through AECMA . organisation,

- A common registration by PECHINEY and BRITISH ALUMINIUM Ltd of Mod. 2650 shall be asked at the Aluminium Association,

- A commercial brochure shall be prepared by BRITISH ALUMINIUM Ltd and PECHINEY.

Besides, complementary Research and Development actions are a)solutely necessary before the introduction of the new alloys into any industrial application :

- Study of the influence of process and chemical composition variations on properties in order to achieve the industrial scale production of sheets ar d plates with a high level of reliability and reproducibility,

- Production of design allowable, in order to complete the specifications and to insure the promotion of the new alloys

- Study of the effect of the manufacturing process on properties,

- Development of manufacturing process and optimisation of chemical compositions for forgings and extrusions.

It has 10 be clearly stated that the application of the new alloys to general engineering will I1OL bet possible without an extra support to produce design allowables. As a matter of fact, unless aerospace companies, enterprises working in the general engineering field have limited R & D capabilities and cannot wait for, nor pay for the establishment of these design val ucs. These companies can only use products that are well established and that have been qualified for similar applications.

6 - CONCLUSIONS

- At the end of this R &D project, 2. alloys / families Of alloy were developed and tested **at the laboratory state that meet all of the original target properties, hut some** variations in properties between task 1 and task 2 were observed which are not completely understood and questioned for the, scaling up to industrial products and reproducibility.

- The main problems encountered in the technical development. were a time scale too short, fundings too limited for the basic understanding work and difficulties in the exploitation of creep results because of the difference in creep tests methodologies.

- Further improvements may be done *through the* influence of manganese + silicon vs nickel and of process parameters (homogenisation) which would need to be assessed with complementary scale experiments.

- Before transferring. the results of this reaserch to industrial applications, further industrial developments are still required concerning the fabrication of optimised products in real' industrial conditions and the production of design allowables.

- Complementary R & D work is still needed with forging and extrusion companies to adapt the chemical composition and the process to these products.

- Two patents have been applied by PECHINEY and AEROSP ATIALE as a result of this R & D project: one on the composition of the 2650 alloy and one on the application of this alloy to structural components of aircrafts.

ACKNOWLEDGEMENTS

This project was funded by the Commition of the European Community as part of the BRITE-EURAM Programme (Project no : BE 5118, Contract BREU CT '120153, Title : Development of a New Aluminium Alloy for Use at 150°C).

Besides, we would like to adress special thanks to our colleagues from BRITISH ALUMINIUM Ltd, BRITISH AEROSPACE AIRBUS, DAIMLER BENZ AG, DAIMLER BENZ AEROSPACE AIRBUS, DASSAULT, DRA, ISTRAM, MIRTEC, ONERA and PECHINEY for their kind and profitable collaboration and to Dr Schmidt, from the CEC DG XII, for his help and fruitful discussions during the project.

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