Cost-Effective Manufacturing of High Performance Power Generation Combustion Turbine Components Using the Fabricated Component Method

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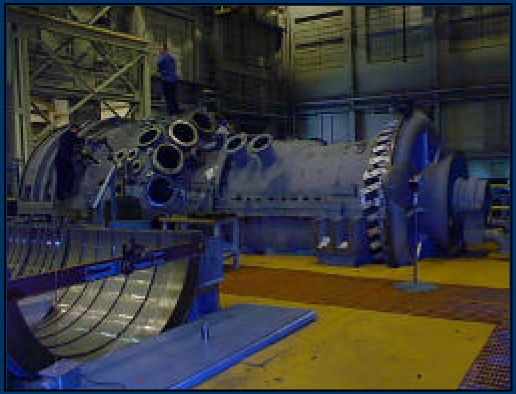
Power Generation Materials
- The Current Drivers -

Cost Effective Manufacturing Processes

Higher Temperature Materials



Lower Plant Capital Cost

More Fuel Efficient Operation

Lowest Cost of Electricity!

Cost Effective Maintenance

Reduced Emissions & Clean-up Costs

Better Inspection and Improved Repair Processes

Uncooled Combustion Systems

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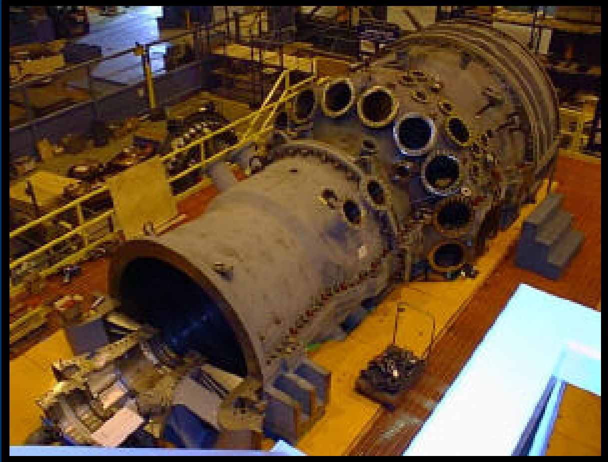
Fabricated Blade Approach to Low Cost High Yield Manufacturing

- Advanced blade designs demand
  - highest strength alloys
  - thin walled structures/complex cooling
  - zero tolerance to core shift
  - distortion-free long parts
- Single piece casting technology must be improved for acceptable yield production of blades & vanes
- Repair/refurbishment is more important as component cost increases



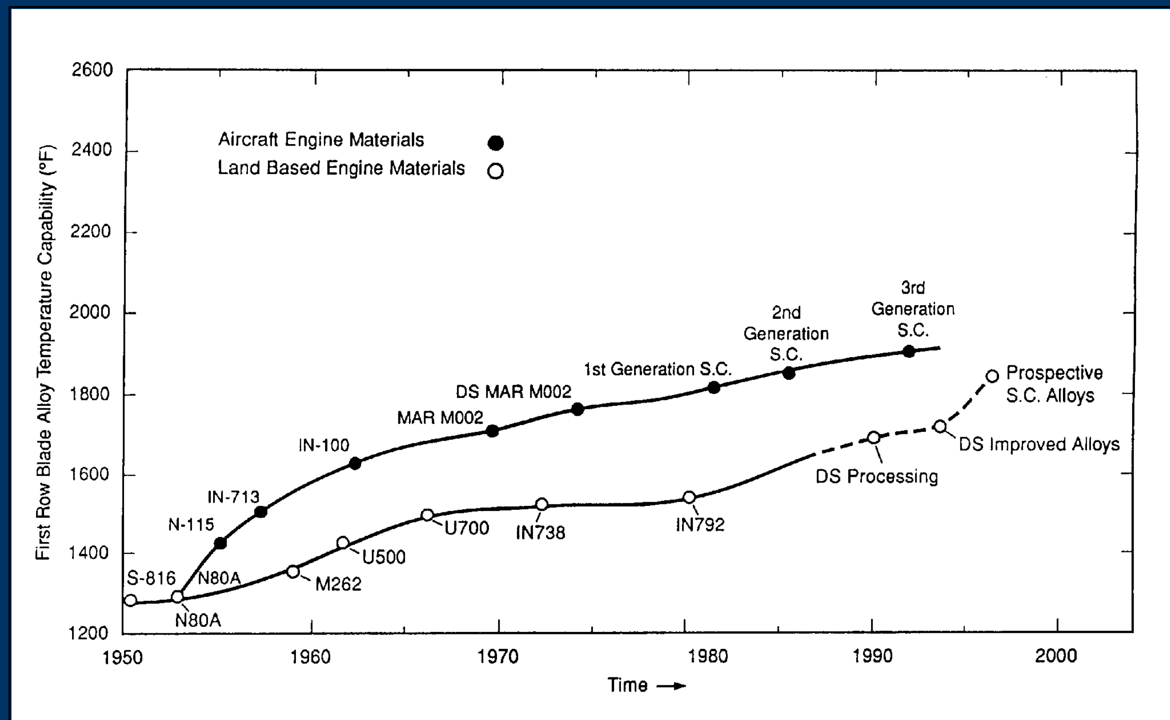
Bonded Turbine Components for Improved Performance

- Fabricated concept utilized transient liquid phase bonding approach developed in 1970's by P&W due to low yield of single piece castings
- 'Bonded blade' technology for land based turbines concept proven in Westinghouse-PCC NIST-ATP Program (1995-1998)
- 'Bonded blade' technology to be implemented in Siemens Westinghouse DOE-ATS-ATAMT Program (1999-2001) - target implementation is ATS R1 components

Gas Turbines - Key Materials Issues

Material Drivers
- Cost vs payoff
- Development cost
- Not weight !

Current Needs
- Gas Ts to 2600°F
  - internal cooling
  - coatings
  - advanced materials with critical properties:
    - ✓creep strength
    - ✓thermal fatigue strength
    - ✓oxidation resistance
    - ✓hot corrosion resistance
- Target life > 50,000 hrs (inspection @ 24,000 hrs)



Current Engines
- Thermal barrier coatings
- G-Class engines use DS alloys
- ATS-Class engines will use SC alloys

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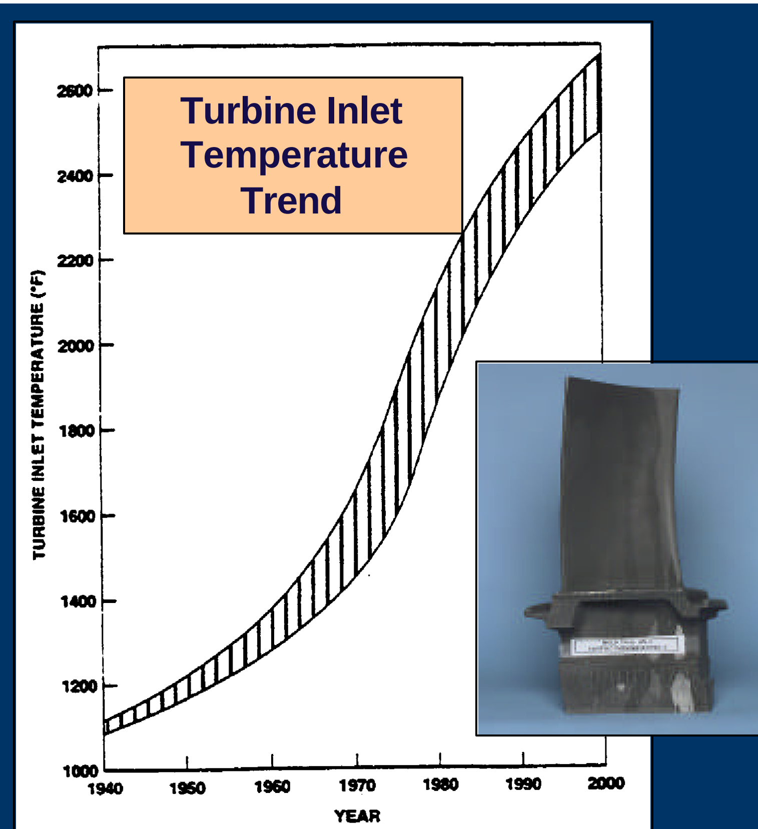
Gas Turbines - Advanced Airfoil Materials

- **Turbine inlet Ts have increased by 900°F (500°C) in the past 30 years**
  - 70% due to more efficient design of air cooling & use of ceramic thermal barrier coatings
  - 30% due to improved superalloys
- **Alloy development path should follow aeroengine materials**
  - DS ➔ 1st generation SC ➔ 2nd generation SC
- **Maintain properties at elevated Ts**
  - creep capability
  - LCF (transverse LCF!)
  - oxidation/hot corrosion
- **Producibility requirements**
  - cost effective
  - high yield
  - minimum 'learning curve'



But the producibility of large, complex structures in high performance alloys is a cost & yield issue!

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Blade & Vane Development for Advanced Land Based Turbine Engines

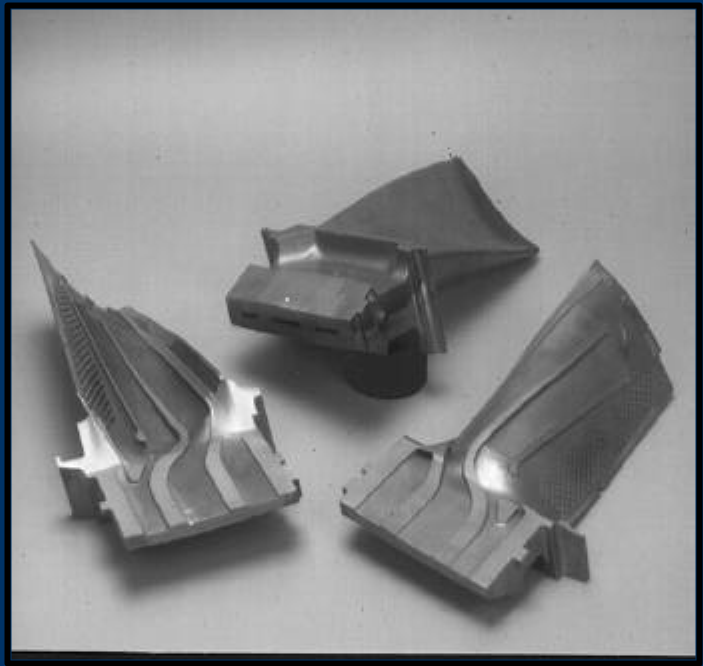
- Higher power and high efficiency gas turbines will operate at higher gas temperatures
- Next generation gas turbines will need materials with higher temperature capabilities
- To avoid creep failure at high temperature, new *SINGLE CRYSTAL* materials are needed for hot end components
- Defect free *SINGLE CRYSTALS* must be cost effectively available

Single Crystal Blade Technology

- Technology developed by DoD and now in widespread use in aero-industry
- Power generation application requires a significant scale-up
- Power generation implementation requires cost effective production at introduction

Power Generation Gas Turbine SC Materials
- State-of-the-Art -

- DS castings of 1st generation alloys are in production ….
- ….but scale up produced the 'hafnium banding' issue
- 1st generation SC alloys have been cast as simple, smaller blades
- 2nd generation SC alloys are prone to freckling, Rx and secondary grain defects in large sizes
- 2nd generation SC alloys can be cast as large, simple sections
- Complex blades and vanes may require alternative processing - 'bonded components'



SC cast blade halves and a 'bonded SC blade'

Alternative process is needed to produce defect free high performance SC blades at cost effective prices

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Development of Land Based Engine Blades & Vanes

- Require defect free structures of SC or DS materials
  - grain boundaries, freckles, misorientations
- Incorporate precise features for improved aerodynamic and thermal performance
  - external profile, wall thickness
- Production problems scale with size - often with volume!!

We need a quantum improvement in casting technology to develop acceptable yields!

- Development costs (=learning by producing bad parts) are exceptionally high for land based engine parts

We cannot afford aircraft parts learning curve!

Grain Boundary & Freckle Defects in Single Crystal Casting

Scale Up Issues for Casting of SC Engine Blades & Vanes

Casting Yield

Aircraft	Land Based
30 parts/mold	3 parts/mold
90% casting yield	90% casting yield
3 defects = 3 defective parts	3 defects = 3 defective parts
27 good parts	***0 good parts***

► We need a quantum improvement in casting technology to develop acceptable yields!

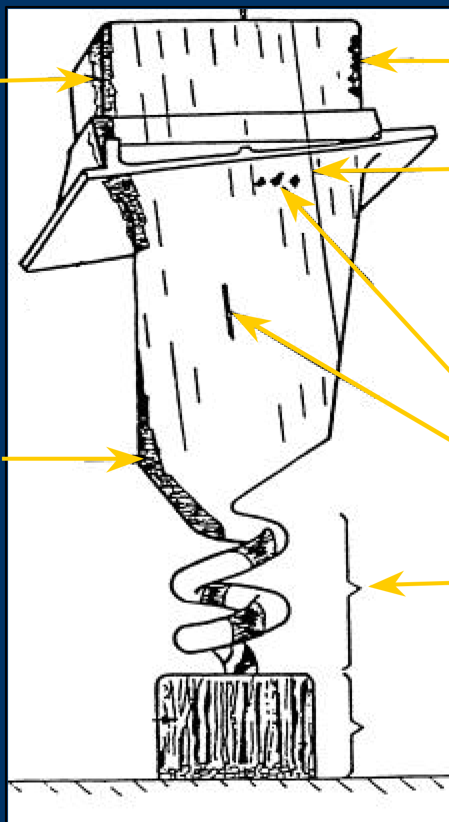
Cost of Scrap

(during early development of new...)

Aircraft	Land Based
weight of blade ~ 1 lb	weight of blade ~ 30 lbs
cost of blade ~ $200	cost of blade ~ $6,000
cost of blade at 90% yield ~ $220	cost of blade at 90% yield ~ $7,000
cost of blade at 20% yield ~ $1,000	***cost of blade at 20% yield ~ $30,000***

► We cannot afford aircraft parts learning curve!

Power Generation Gas Turbines
- SC Material Issues -



Potential defects
in single crystal castings

In reality, the scale-up of aeroengine technology to power generation applications is NOT simple or cheap!

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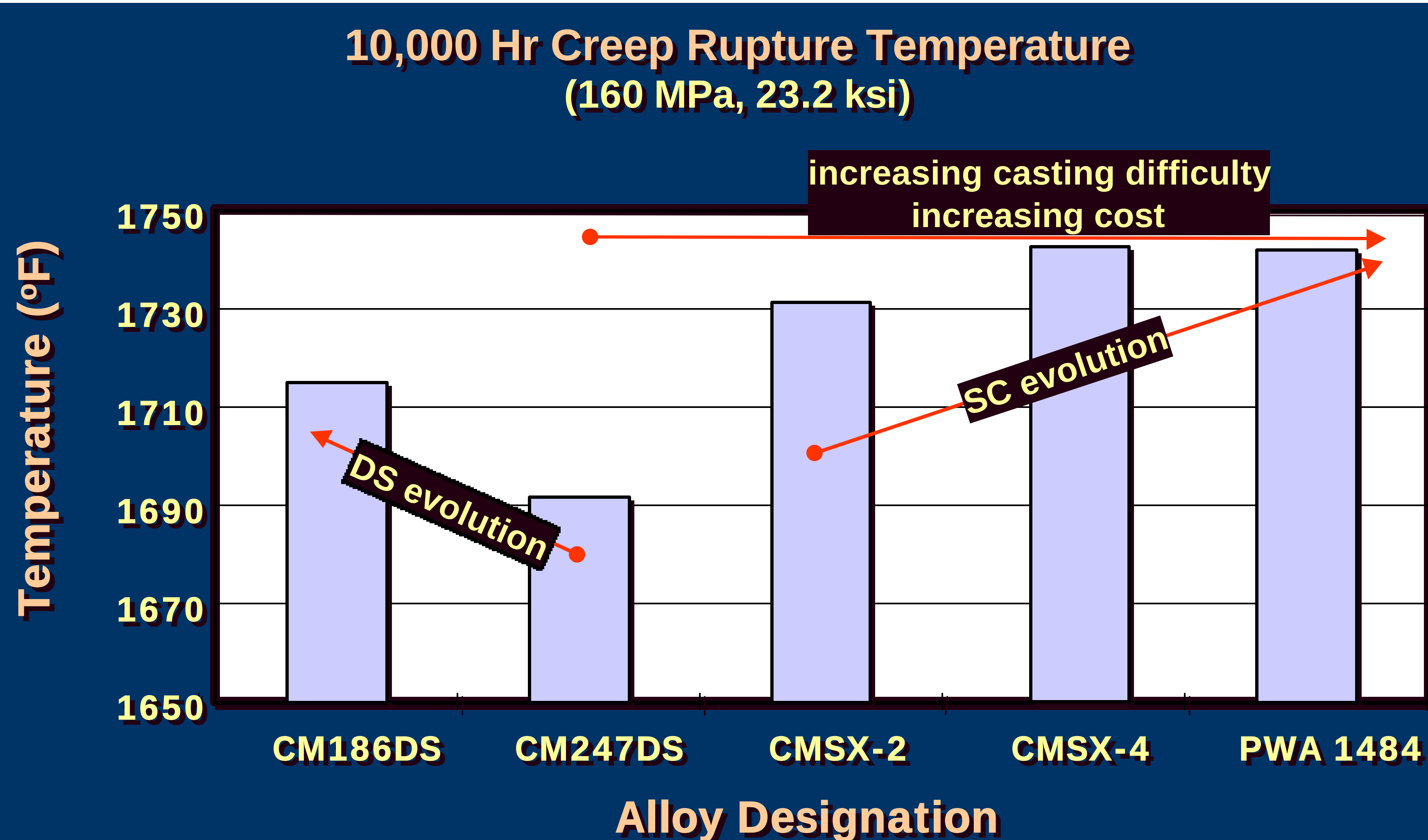
Gas Turbines - Advanced Alloys



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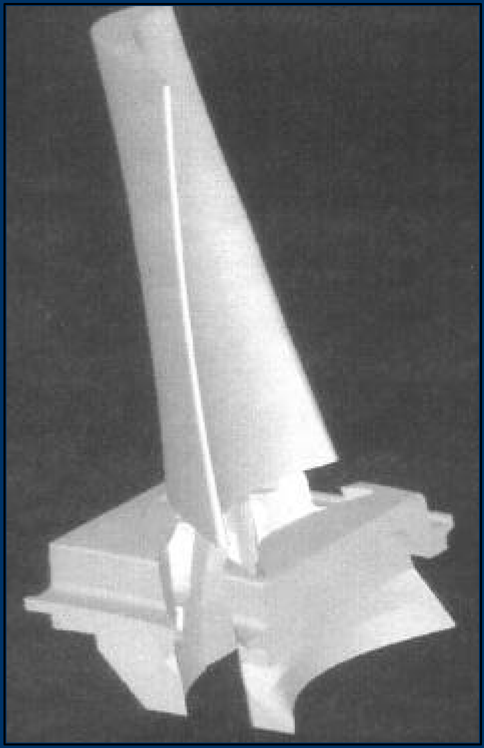
Fabricated Component Approach to Low Cost High Yield Manufacturing

- **Advanced blade designs demand**
  - high yield casting of large mass pieces
  - distortion free long parts
  - thin walled structures and intricate cooling
- **Bottom line: complex geometry SC castings for power generation turbines may not be possible as single piece castings è fabricated components!**
- **Single piece SC components experiencing VERY low casting yields because:**
  - large section sizes & section size changes induce defects
  - very precise internal cooling geometries cannot currently be cast into single piece SC large parts
  - thin wall structures cannot be cast as single piece components
- **Fabrication concept utilizes Transient Liquid Phase Bonding approach developed in 1970's by P & W due to low yield of single piece castings**
  - assume 90% casting yield for smaller segmented pieces
  - assume 90% bonding yield



80% part manufacturing yield

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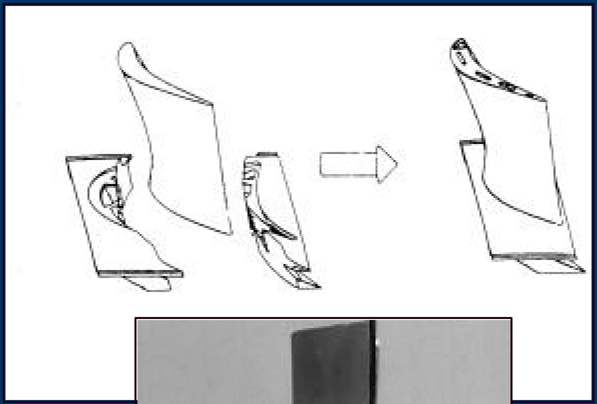
NIST - ATP
Fabricated Blade Development Program

- **Blade Design/Redesign**
  - 'Segmentation process' of an existing blade design
  - Placement of bond planes in insensitive locations
  - Design for manufacturing
  - Modification of design to incorporate processable features
- **SC Casting Development**
  - Quality casting of single crystal portions
  - Defect free material
  - Precise profile control
  - Demonstration of quality/yield
- **Bonding Development and Verification**
  - Identification of bond material and processes
  - Optimization of processing
  - Verification of performance
  - Development of property database
- **Full Scale Bonding**
  - Bond blade segments
  - NDE evaluation
  - Sectioning and destructive evaluation



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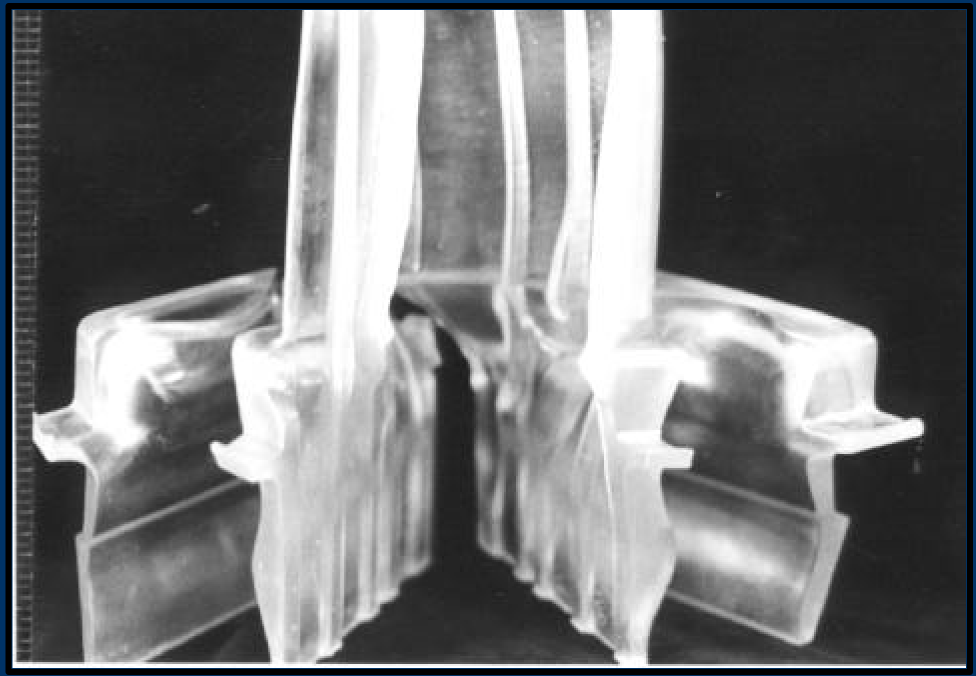
Fabricated Blades Design Process

- Segmentation into castable segments
  - root(s), air foil
  - vertical segments
- Identify low stress planes/surfaces
- Evaluation subdivisions of initial segmentation processes
- Elimination of stress concentrations and protrusions
- Assessment of castability and application of bonding material
- Iteration



Stereolithography model of four-piece blade segmentation

Manufacturing trade off: smaller pieces increase casting quality but require more bonds

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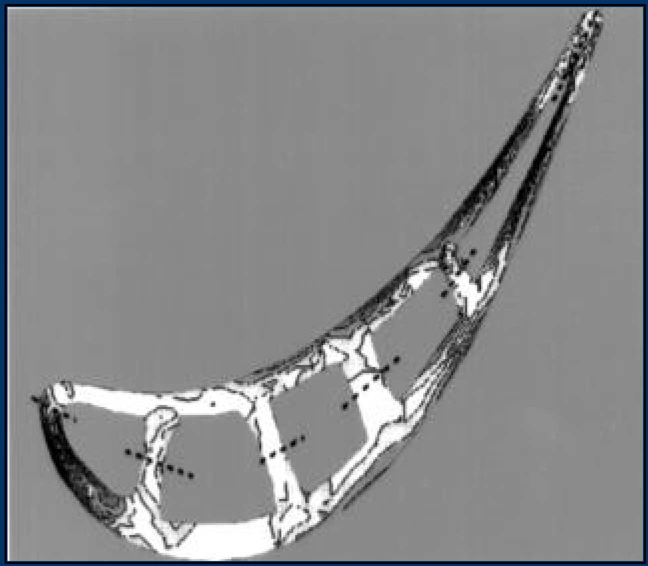
Fabricated Blades Design Results

- Blade stress modeling using FEA capability
- Assess stresses across camber line for primary segmentation
- Consider moving segmentation plane to avoid local discontinuities and stress concentration
- Assess transverse stress across segmentation plane
- Consider secondary segmentations
- Compare assessed stresses across proposed bond plane with respect to:
  - design allowables for creep, fatigue, etc.
  - database properties of SC alloy



FEA output of stress pattern of blade cross section showing minimum transverse stress near the blade camber line

Assessed stresses perpendicular to the bond plane for segmented candidate blade are less than 25% of properties of CMSX-4 SC alloy

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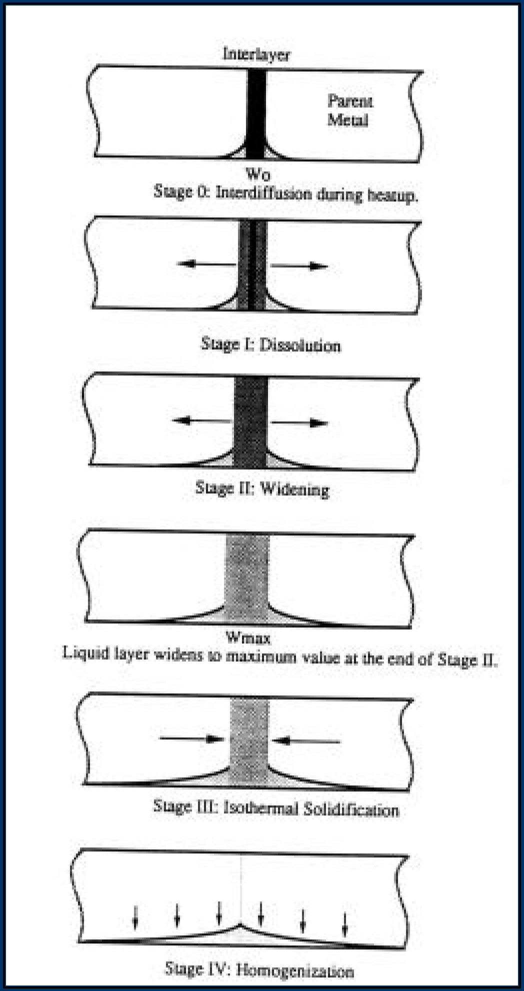
Single Crystal Casting of Blade Halves

- Single crystal casting technology developed for 'halves of blades'
- Blade halves cast using coreless 'dip mold' processing
- Casting parameters developed by PCC to produce 'good grain'
  - good grain produced in airfoil
  - minimal freckles in root
- Processing conditions developed based upon computer modeling analysis
- Cast segments incorporate excess stock for pre-bond processing

- Trial 6 casting -
single crystal convex blade half

Transient Liquid Phase Bonding Concept

- Bonding strip contains high diffusivity melting point depressant (B)
- During heat ramp and isothermal hold, diffusivity of B causes initial widening of melted zone
- During further isothermal hold, dilution of the melt zone causes re-solidification
- Controlled impingement of the solidification front produces a good bond
- Chemistry of bond region is controlled by the chemistry of the foil and the base metal



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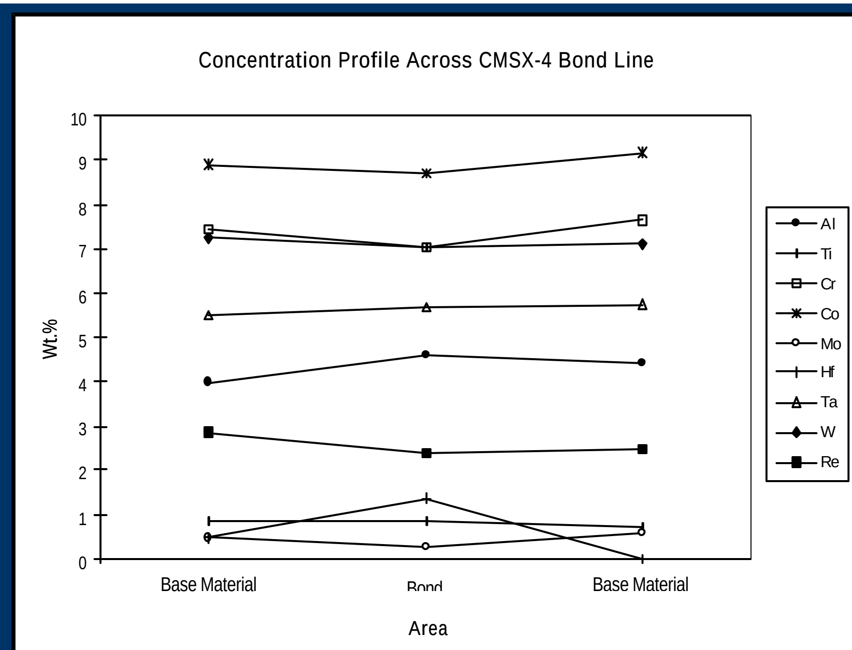
Transient Liquid Phase Bonding Concept

- **Transient liquid phase bonding can produce the highest quality bonds in high strength metals and alloys**
- **Developed in the 1970’s by P & W for aircraft engine components - 90% of base material properties attainable!**
- **Bonding media contains melting point depressant and a carefully selected ‘subset’ of the parent metal chemistry**
  - **little or no Al & Ti to deter eutectic g’ formation**
  - **little or no slow diffusing elements**
  - **optimum level of B**
- **Can obtain chemically and structurally homogenous bond joints**



Electron microprobe chemical analysis across the bond line

How do you bond COMPLEX LARGE SINGLE CRYSTAL (CMSX-4) components?

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CMSX-4 Bonding Development Issues for Fabricated Blades

- Selection of bonding foil
  - Commercially available foils
  - Development of custom bonding material
- Development of bond cycle/solution heat treatment process
  - Solution treat CMSX-4 casting
  - Homogenize bond zone segregation
- Development of gamma prime microstructure in bond zone
  - Cuboidal 0.5 μm gamma prime desired
  - Similarity to optimum base metal structure
- Mechanical performance of bond materials and process
  - Down select based upon microstructure
  - Tensile and creep screening tests
  - Select ‘best’ option
- Mechanical property database
  - For ‘best’ option
  - Full design database of tensile, creep, and fatigue properties

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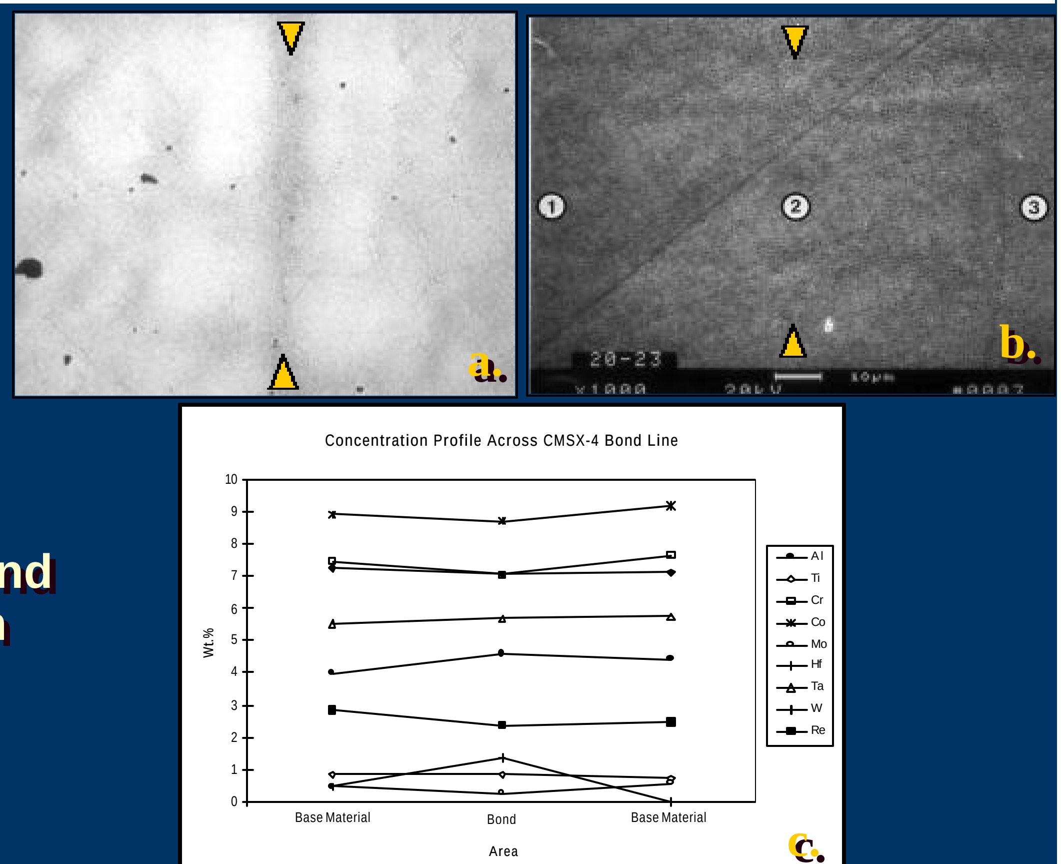
Microstructural Evaluation of Bonding Processes

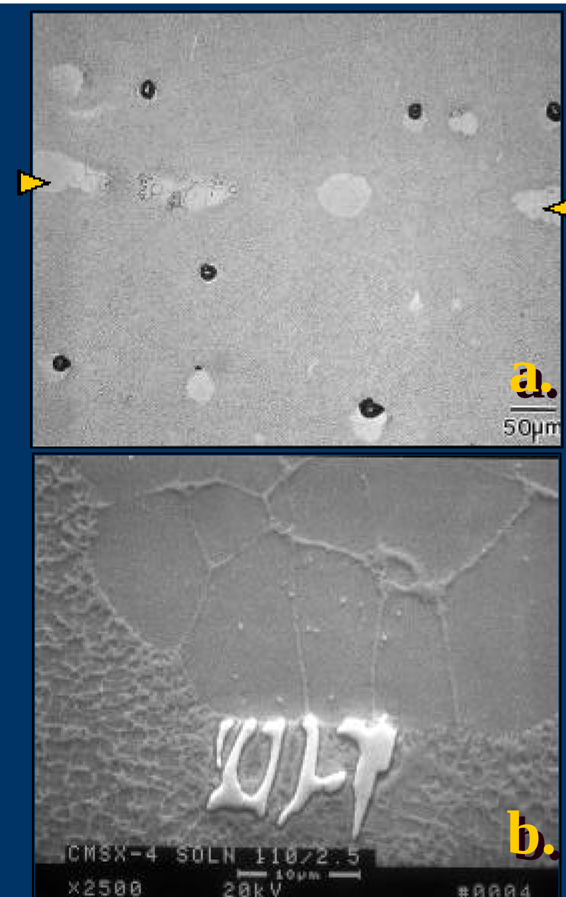
- All commercial foils produced reasonable bond chemistries and structures - no need to develop CMSX-4 specific foil
- Bond zone width is controlled by B content and bond temperature
- Bond time is excessive for solidification but allows solid state diffusion
- Metallic element composition of bond zone is affected by foil composition and dissolution from base metal
- Microstructure of bond zone is influenced by bond zone size and segregation and by post bond heat treatment
- Bond surface preparation affects bond zone structure



(a) Optical microstructure, (b) g‘ morphology and (c) microprobe chemical analysis across the bond line

Effects of Bonding Foil B Content & Processing Cycle on Bond Zone Microstructure

- **Chemistry of bond zone is due to mutual dissolution of bond foil and base metal**
- **Extent of bond zone dissolution is controlled by:**
  - **thickness of bond foil**
  - **amount of boron in bond foil**
  - **state of base material (as-cast vs. homogenized)**
- **Resolidification of the bond zone produces bond line segregation (Al, Ti eutectic)**
- **Lower boron content foil, homogenized microstructure and higher bond temperature promote segregation in bond zone**
- **Solution treatment after bonding may dissolve bond line eutectics - but its better not to produce them in the first place!**



Formation of deleterious g’ near the bond region

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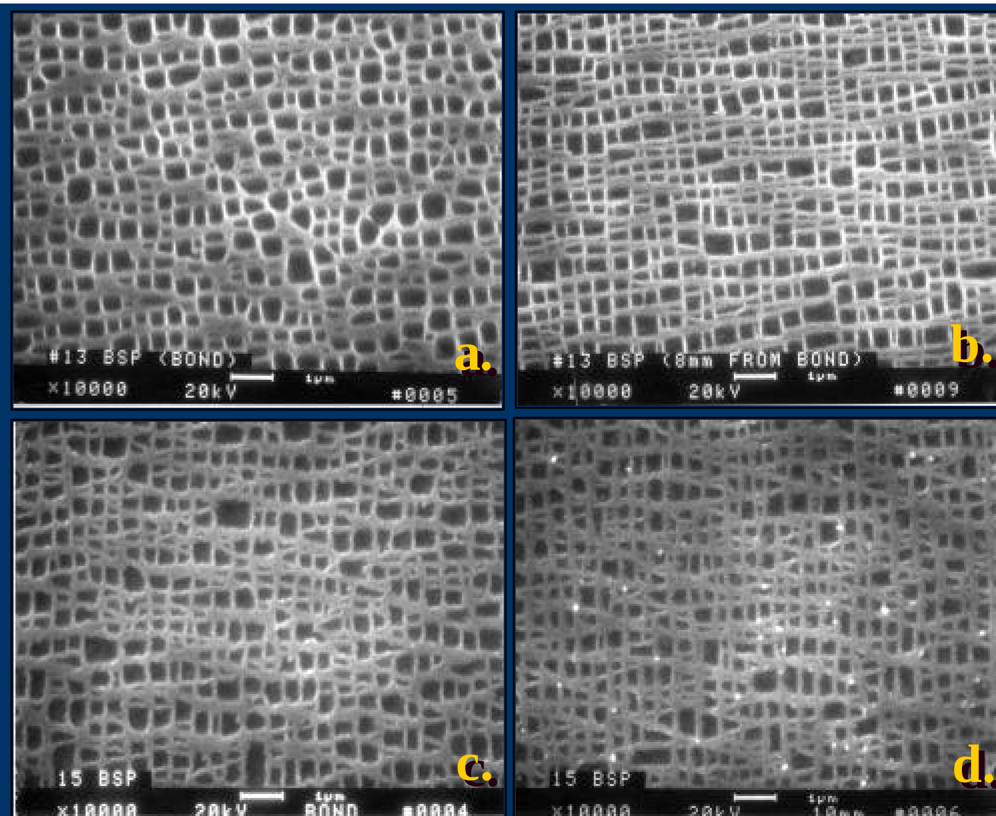
Effect of Foil Chemistry on Bond Zone Gamma-Prime Morphology

- **Elemental content of foil and state of base metal affect the bond zone g’ morphology (after heat treatment)**
- **Matching foil chemistry to base metal improves g’ morphology - Ni-Flex 110 preferred to other foils**
- **Bonding as-cast material followed by solution treatment promotes more cuboidal g’ morphology**
- **Gamma’ shape is controlled by g/g’ misfit….which is a function of local composition**
- **Increased Al content in bond zone promotes increased misfit and cuboidal g’ morphology**



Microstructure of sample D in (a) bond zone and (b) away from bond zone and sample H in (c) bond zone and (d) away from bond zone

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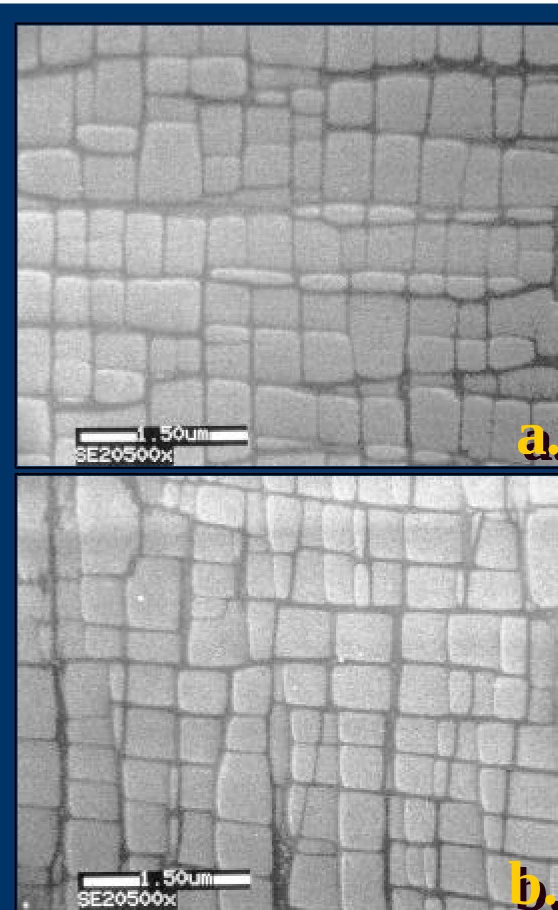
Optimum Gamma-Prime Structure Can Be Produced in the Bond Zone

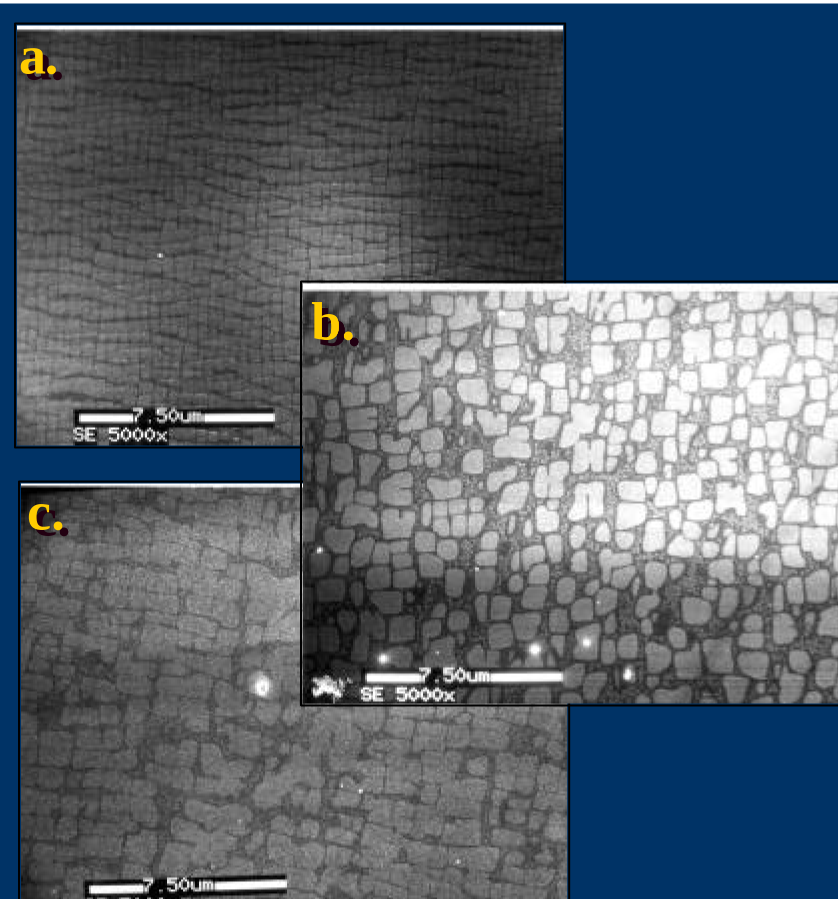
- **Optimum microstructure induced in bond line by:**
  - **1.3% B**
  - **high bond temperature 2250ºF (1232ºC)**
  - **bond in the as-cast condition**
  - **solution heat treat after bonding**
- **Optimum microstructure is produced in both the base metal and in the bond zone**
  - **well aligned gamma prime cuboids**
  - **~ 0.5 mm size cuboids**
- **This sample selected as 'best' microstructure - but carry 3 other heat treatments into mechanical property testing phase**



STEM Micrographs of g' morphology in (a) bond zone and (b) matrix

Down-selected Bonding Processes for Mechanical Properties Evaluation

- **Sample I**
  - **Low B, as-cast, post-bond solution heat treatment and precipitation heat treatment**
  - **Represents the 'best' microstructure**
- **Sample N**
  - **Low B, as-cast, post-bond precipitation heat treatment**
  - **Assess the influence of omitting post-bond solution heat treatment**
- **Sample O**
  - **High B, solution treated alloy, post-bond precipitation heat treatment**
  - **Represents 'best' microstructure for high B and without post-bond solution heat treatment**
- **Sample B** (microstructure not shown but similar to O)
  - **High B, solution treated alloy, post-bond solution heat treatment and precipitation heat treatment**
  - **Represents affect of solution treating segregated microstructure**



Bond region microstructures of samples (a) I, (b) N and (c) O.

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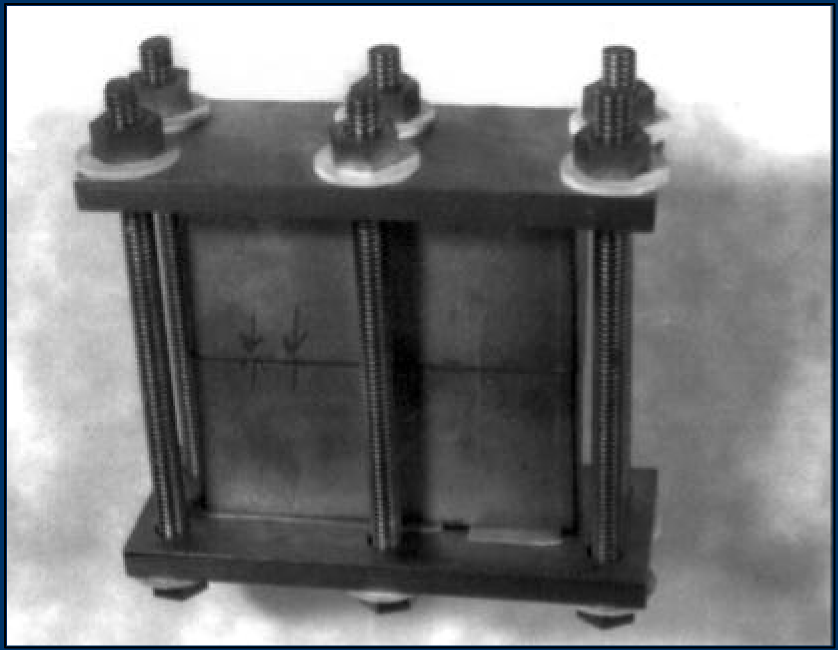
Mechanical Testing Program

- Sectioned slabs, re-bonded to form 76 mm x 76 mm x 9.5 mm slabs
- Slabs bonded in molybdenum fixturing
- Five 9.5 mm x 9.5 mm cross section specimen blanks taken from each slab parallel to growth direction
- Tensile tests conducted at room temperature, 1650°F (890°C) and 1800°F (900°C)
- Creep tests conducted at 1650°F (890°C)/50 and 80 ksi and 1800°F (900°C)/28 and 45 ksi (100 hour and 1000 hour target rupture lives)



Molybdenum fixturing for bonding CMSX-4 slabs for mechanical test specimens

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Tensile Test Results

T K (C, F)	Processing	Failure Location	Y.S. MPa (ksi)	U.T.S. MPa (ksi)	Elongation %	R.A. %
Room						
	Typical Value	Base	896 (130)	931 (135)	14	18
	B - Ni-Flex 110, 2.5%B, S/B/S+P	Base	965 (140)	1,048 (152)	13.5	16.1
	N - Ni-Flex 110, 1.3%B, A-C/B/P	Base	807 (117), 814 (118)	979 (142), 1,082 (157)	14.5, 25.4	15.4, 24.4
	O - Ni-Flex 110, 2.5%B, S/B/P	Base	765 (111)	841 (122)	14.7	17.1
	I - Ni-Flex 110, 1.3%B, A-C/B/S+P	Base	N/R	945 (137)	2.6	6.4
1172 (899, 1650)						
	Typical Value	Base	758 (110)	103 (150)	18	37
	B - Ni-Flex 110, 2.5%B, S/B/S+P	Base	786 (114)	965 (140)	3.4	5.9
	N - Ni-Flex 110, 1.3%B, A-C/B/P	Bond	689 (100), 683 (99)	883 (128), 883 (128)	13.7, 16.5	19.6, 24.3
	O - Ni-Flex 110, 2.5%B, S/B/P	Base	724 (105), 731(106)	896 (130), 903 (131)	22.9, 18.5	34.5, 28.4
	I - Ni-Flex 110, 1.3%B, A-C/B/S+P	Base	731 (106)	731 (106)	1.1	2.6
1255 (982, 1800)						
	Typical Value	Base	655 (95)	682 (125)	18	45
	B - Ni-Flex 110, 2.5%B, S/B/S+P	Base	703 (102)	807 (117)	4.1	6.9
	N - Ni-Flex 110, 1.3%B, A-C/B/P	Bond	510 (74), 572 (83)	710 (103), 683 (99)	10.4, 8.1	16.8, 17.8
	O - Ni-Flex 110, 2.5%B, S/B/P	Base	621 (90), 565 (82)	696 (101), 717 (104)	19.3, 19.5	26.3, 37.2
	I - Ni-Flex 110, 1.3%B, A-C/B/S+P	Base	758 (110), 421 (61)	820 (119), 421 (61)	13.6, 4.6	21.4, 7.9

N/S = Not Specified, N/R=Not Reported, A-C = As-Cast, B=Bond, S=Solution Treated, P=Precipitation Treated

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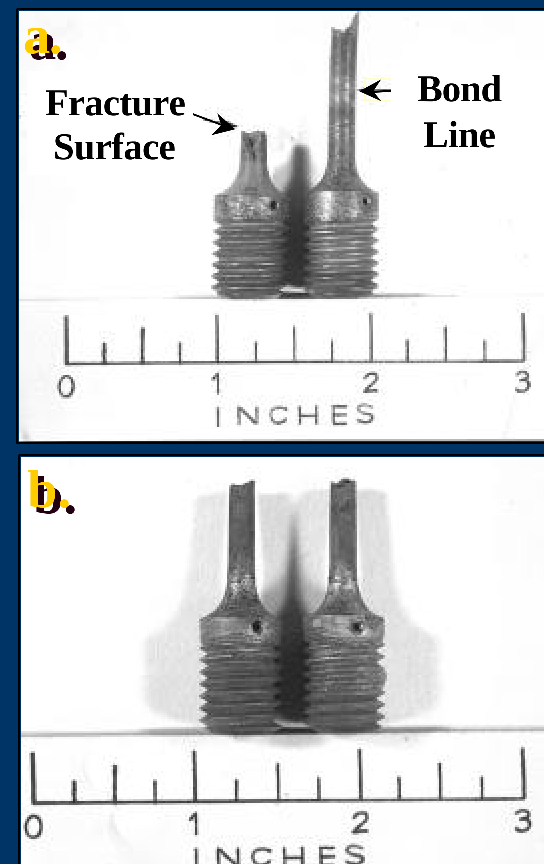
Creep Test Results

- All creep rupture lives were close to or above the targeted 100 hour and 1000 hour lives
- Most of fractures were across the bond zone
- Reduced ductility compared to database CMSX-4
- Creep ductilities are still in the 10% to 20% range

Mechanical properties for all four conditions appear adequate for use in fabricated components



Fractured bonded (a) tensile and (b) creep specimens

Application of Technology for Fabricated Blade Development

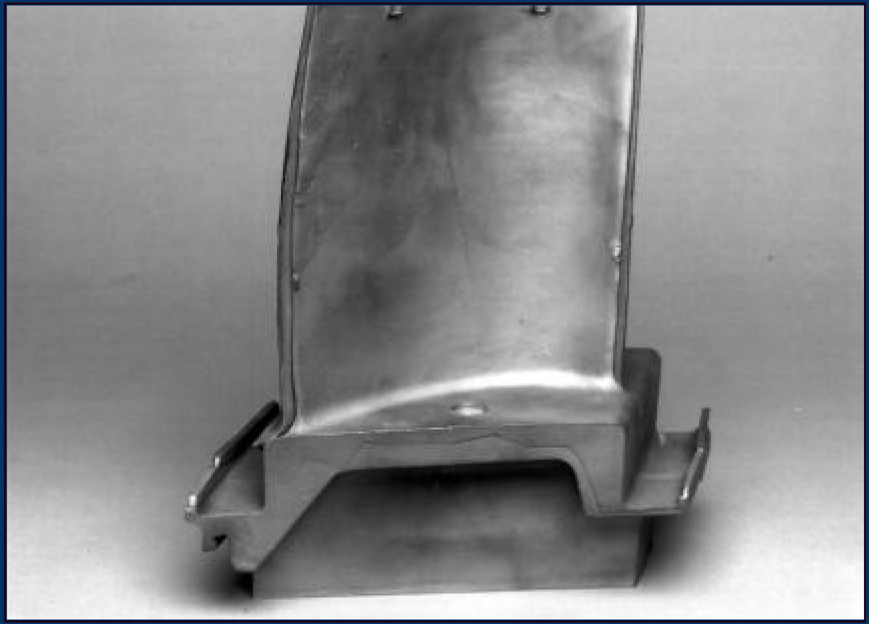
- Utilize process developed via laboratory testing
- Bonding of full sized components
- Develop approaches for processing full sized parts: pre-bond processing, handling, fixturing, evaluation, etc.
- Casting of single crystal blade halves
- NDE/destructive evaluation of bonded blades

Laboratory fixturing for bonding power generation turbine blades

NIST-ATP Program
Full Scale Blade Bonding

Pre-Manufacturing Trial

- Early in program (~ 1 year)
- Identification of manufacturing issues
- F-engine blades
- IN738 CC bonding



Single Crystal Blade Bonding

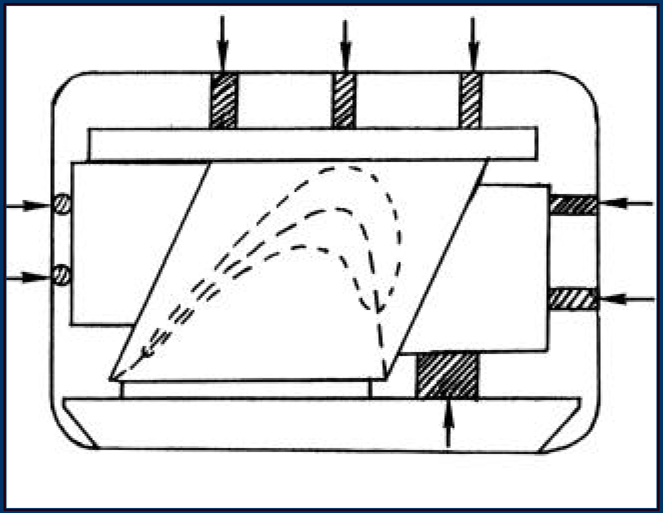
- End of program
- Target quality bonds in SC blade halves
    - G-engine blade
    - CMSX-4 SC bonding

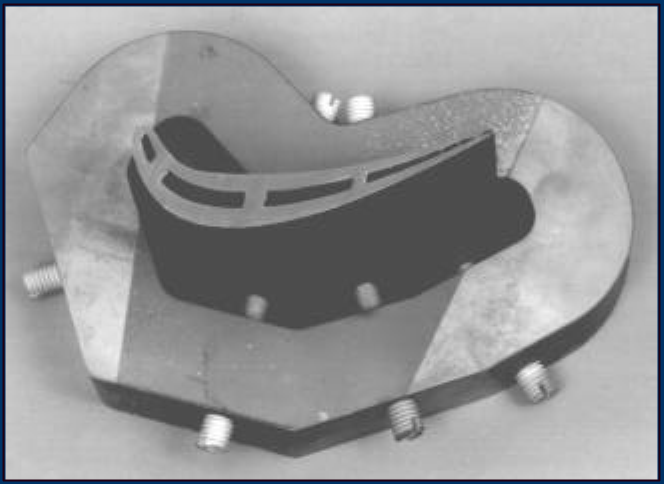
501F and G Full Size Blade Bonding

- Fixture Fabrication -

Purpose: Design/fabricate fixturing for bonding full size 501F R2 and G R1 blades

- 2 F and 2 G blades bonded
- Fixturing designed from electronic cross-section data
- Preplace bond material between blade halves
- Bonding loads generated by differential thermal expansion between blade and fixture components
- Fixtures ensure proper seating of the blade assembly at bonding temperatures
- Bond fixture applies loads normal to bond plane
- 'Point' loading of surface by pins through the yokes
- Ceramic plugs and inconel pins employed to provide load





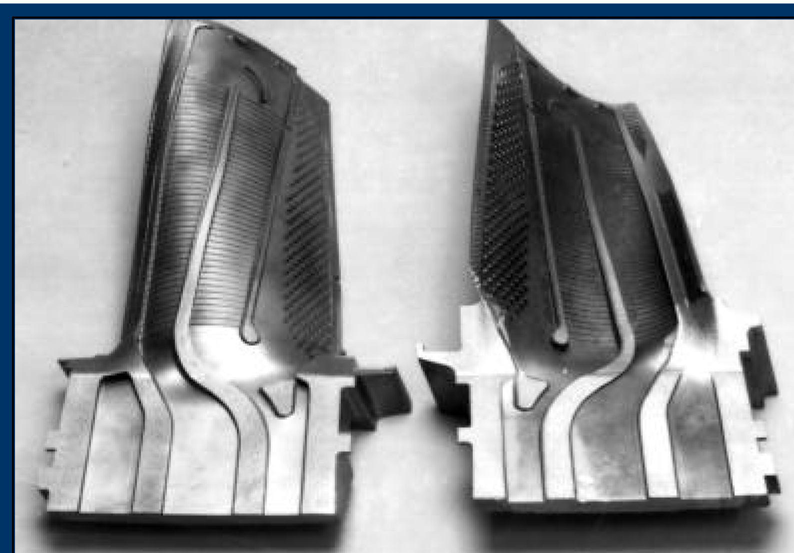
Blade Halves for Full Size Bonding

Pre-Manufacturing Trial

- ‘Blade halves’ extracted from scrap blade castings
- Need to produce matched blade halves
- Produce one blade half from one whole cast blade
- Approximate blade halves produced by cavity EDM
- Pre-bond processed to provide appropriate fit ups

Single Crystal Blade Bonding

- Blade halves cast as matched pairs
  - Mated wax patterns
  - Cast foam patterns



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Full Sized Blade Bonding Results

- 501F R2 and 501G R1 blades bonded
- Pre-bond processing of blade halves developed for tight gap fit-up
- Blade fixturing designed by production plant (facilitates transition to manufacturing)
- Temperature and vacuum control during bond cycle ensures good bonds
- Proof of concept demonstrated to manufacturing
- Production support NDE method verified

It is feasible to produce high quality bonds in large complex components!

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NIST - ATP Bonded SC Components
- Technology Status -

- Blade design
  - two piece and four piece concepts developed
  - CAD integrated with SLA model making for mold development
- Single crystal casting
  - improved productivity and airfoil SC grain quality
  - profile tolerance issues remain
- Single crystal bonding
  - foils and thermal processes developed for bonding CMSX-4
  - acceptable mechanical properties demonstrated in bonded CMSX-4
- NDE of bond lines
  - promising signal/microstructure correlations developed
  - correlation of NDE signal/mechanical behavior
- Full part bonding
  - full sized fixturing developed
  - demonstrated processing for existing CC blades
  - parts pre-processing needs identified
  - full scale CMSX-4 blades bonded

NIST Bonding Program - Progress & Issues

Progress

- Blades can be successfully segmented along low stress, easy to bond planes
- Successful bonding of segmented blade design can be accomplished with minimal loading across bond plane
- Commercial foils are available for bonding
- Correct thermal processing can produce excellent material structures in the bond regions
- Bonded properties which met design requirements were produced by several processes
- Full size SC blade bonding is feasible but there are still ‘issues’

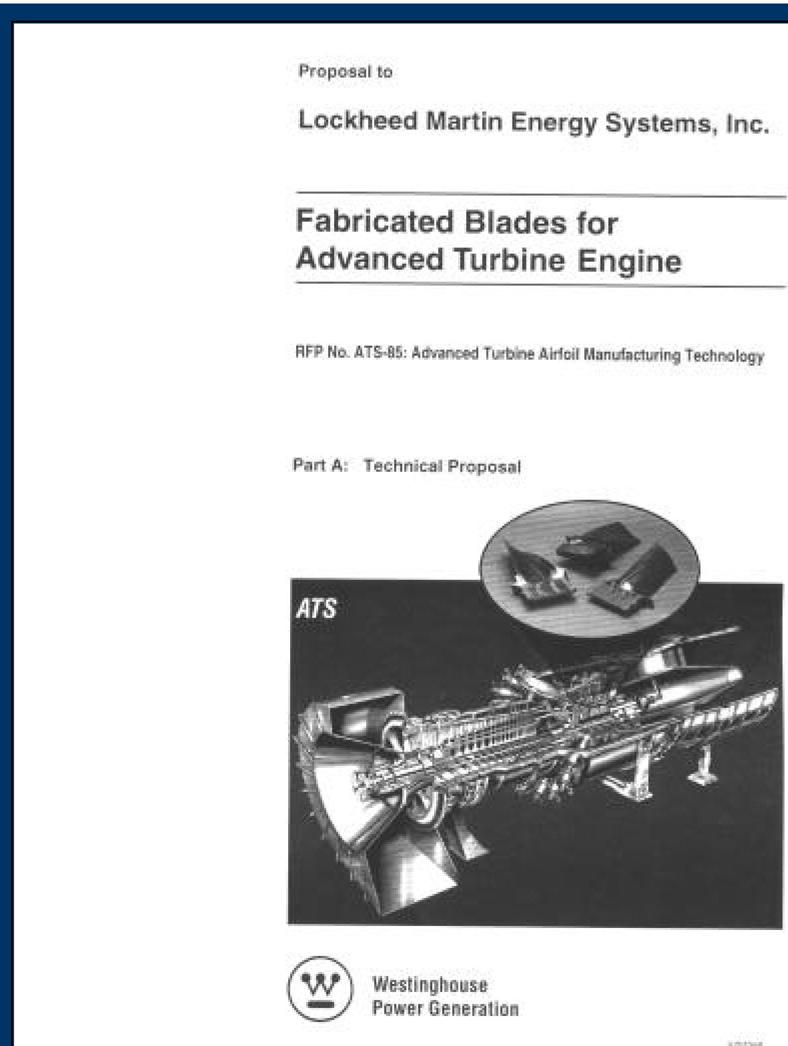
Issues

- Precise casting of blade halves for good fit-up has not been achieved
- Acceptability of mechanical properties?
- Repeat testing with known SC quality and orientation?
- Development of reliably clean bonding surfaces after pre-bond processing
- Reproducibly eliminate cleaning and handle defect formation and subsequent surface RX

Prototype Fabricated Component Implementation

DOE ATS
Advanced Turbine Airfoil Manufacturing Technology (ATAMT) Program

- Develop manufacturing process for prototype Siemens Westinghouse advanced components
  - target applications
    - ✓ ATS R1 thin wall blade
    - ✓ ATS R1 thin wall vane
  - ATAMT proposal submitted January 1998
    - ✓ program awarded November 1998
    - ✓ planning phase initiated April 1999
    - ✓ experimental phase initiated October 1999


Proposal to

Lockheed Martin Energy Systems, Inc.

Fabricated Blades for
Advanced Turbine Engine

RFP No. ATS-85: Advanced Turbine Airfoil Manufacturing Technology

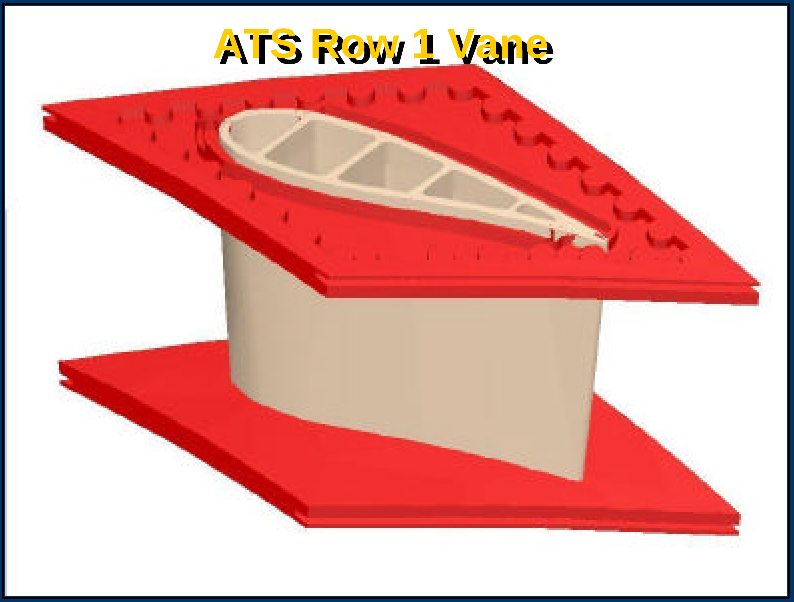
Part A: Technical Proposal

Westinghouse
Power Generation

SIEMENS Westinghouse

Fabricated Vanes for Advanced Turbine Engines

- Program start April 1st, 1999
- Originally targeted ATS blades
  - R1 thin wall
  - R2 thick wall
- Targeting application is thin wall vanes
  - ATS R1 vane
  - also includes 'SuperG' engine early commercialization
- Alternative to single piece production
- Develops production ready transient liquid phase bonding process for real vanes
- Integrated team with manufacturing (Howmet for casting + SWPC Hamilton)
- Targets delivery of prototype engine ready vanes



SIEMENS
Westinghouse

DOE - A T A M T Program Team

Prime Contractor/Program Management

Siemens Westinghouse

Program Objectives - Ensure program focus on ATS vane product. Ensure financial and schedular.

Parts Design

Siemens Westinghouse CT Engr.

Technology - Design of land based CT components.
Program Objectives - Develop design for manufacturing of ATS vane.

Casting Vendor

Partners: Howmet

Technology - Casting of SC subcomponents.
Program Objectives - Develop high yield castings of vane subcomponents in a production ready, qualified process.

Parts Manufacturing

Siemens Westinghouse Hamilton

Technology - Machining, joining and forming of turbine components.
Program Objectives - Manufacturing technology to ruggedize and qualify part bonding process.

Bonding Developer

Partners: Siemens Westinghouse (Orlando and STC)

Technology - Bonding of SC subcomponents. Large size bonding of land based components.
Program Objectives - Develop processes to bond SC materials. Develop basic processing route for bonding full sized blades. Assess quality of bonded structures and parts.

Support Technologies

Partners: Turn-Tech, CTC

Technology - Subassembly pre-bonding processing, casting and heat treatment modeling support.
Program Objectives - Develop subassembly processing to ensure good fit up for bonding. Optimize heat treatment cycle of bonded parts.

SIEMENS Westinghouse

Fabricated A TS Components

Proposed Program Major Technical Activities

- Design of component and subassemblies: for castability, bondability and performance/properties
- Casting of subassemblies: for material quality, for parts tolerance and profile
- Bonding of advanced SC materials, CMSX-4: for simple and complex joint geometries
- Pre-bond processing of subassemblies: for fit up and mating of subassemblies
- Manufacturing process and equipment: for a reliable production viable process
- Qualified manufacturing and inspection processes: for acceptance of parts

Expected Key Developments

- Develop fabricated component designs for selected ATS vane
- Demonstrate novel cost effective casting processes for defect free SC thick and thin wall subcomponents
- Develop bonding for thin wall structures
- Demonstrate reliable bonding for SC material and complex joint configurations (e.g. orthogonal joining)
- Develop pre-bonding processing for improved parts fit up and more reliable bonding
- Develop production ruggedized, bonding based component manufacturing processes
- Qualify manufacturing process for ATS components

Fabricated Components - Current Status

- Single piece cast components still have high cost and low yield
- Small piece, moderate complexity SC castings can be made in high yield
- Transient liquid phase bonding processing proven to produce bonds in excess of requirements
- Full scale bonding processes demonstrated!
- Bonded component technology concept has been shown to be viable for large utility size gas turbines
- Concept to be implemented in real parts prototyping for ATS engine
- Commercialization to follow prototyping based upon IP (3 patents applied for/developed in NIST-ATP program)

Fabricated components can provide a cost effective route to developing and manufacturing large size advanced gas turbine hot section components

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Power Generation Materials
- The Current Drivers -

Cost Effective Manufacturing Processes

Higher Temperature Materials

Lower Plant Capital Cost

More Fuel Efficient Operation

Lowest Cost of Electricity!

Cost Effective Maintenance

Reduced Emissions & Clean-up Costs

Better Inspection and Improved Repair Processes

Uncooled Combustion Systems