CSIRO research on materials and devices for extreme environments:
Using a systems approach to identify how to invest

Dr Cathy Foley | Science Director and Deputy Director Manufacturing
3 May 2016
Australia’s innovation catalyst
Example of a sensor in an extreme environment
3D printed sternum
Detection that maps 3D environments
Radio telescopes including the SKA
Team CSIRO

- 5319 staff
- $1 billion+ budget
- Working with over 2800+ industry partners
- 55 sites across Australia
- Top 1% of global research agencies
- Each year 6 CSIRO technologies contribute $5 billion to the economy
Some stats

1854
patents
Biggest patent holder in Australia
30% involve collaboration

150+
spin-out companies
worth $1bn in market capitalisation

300
licenses
Most with Australian companies

WiFi
Extended-wear contact lenses

Aeroguard
Landtem
RAFT
Zebedee

Globally our publications are
Top 1%
in 15 of 22 research fields

1,200+
schools
benefit from our scientists
in schools program

200,000+
people visit our public facilities and visitor centres
Our business units and focus areas

- Agriculture
- Energy
- Food and Nutrition
- Health and Biosecurity
- Land and Water
- Manufacturing
- Mineral Resources
- Oceans and Atmosphere
- Astronomy and Space Science
- Australian Animal Health Laboratory
- Data61
- Marine National Facility
- National Computing Infrastructure
- National Research Collections of Australia
Strategic actions to deliver impact

Team CSIRO
Excellent science
Inclusion, trust & respect
Health, safety & environment
Deliver on commitments

Customer first
Breakthrough innovation
Global outlook, national benefit
Collaboration

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CSIRO Manufacturing
Advanced Fibres and Chemical Industries

To support the long term competitiveness of Australia’s cotton, carbon fibre and chemical industries through strategic partnerships and the delivery of resource efficient breakthrough technologies.

140 FTE
Program Director: Greg Simpson

Advanced Fibre Innovation Group
Group encompasses fibre science and characterisation. The work will focus on carbon fibre manufacture and characterisation, post harvest cotton research and innovation and advanced fibre manufacturing and performance, particularly working with Deakin University. (40FTE, Waurn Ponds)

Chemical Processes and Industrial Biotechnology
Group includes the capabilities of Organic, Polymer and Process Chemistry and will aim to establish strong links across CSIRO to the agricultural, food and industrial biotechnology communities. A focus will be on the convergence of chemistry and biological skills to solve industry problems. (50FTE, Clayton)

Materials Science for Energy and the Environment
This group will use the capabilities in advanced and functional materials, nanostructured and hierarchically designed materials and inorganic chemistry to provide solutions to industry. A focus will be building links to the energy and environmental users of materials science. (50FTE, Clayton)
Continuous Metal Production
Alloy Design, and metal production including bulk metallic glasses via continuous production methods that are either melt or non-melt processes. Core competencies are kinetic metal production and powder processing to product including surface protection. 1) Continuous Kinetic Metal Production, 2) Alloy Design 3) Metal Protection

Additive Manufacturing
All aspects of additive manufacturing including feedstock, online measurement, industry engagement, metallurgy and casting including surfacing for functional surfaces or surface improvement. 1) Fusion AM, 2) Solid State AM, 3) Surface Modification, 4) Continuous Processing

To help organisations capture opportunities in the face of a changing metals industry, through innovative sustainable processes and high performance alloys and technologies.

60 FTE
Program Director: John Barnes
To support the adoption and integration of transformational technology in Australia’s manufacturing industry, through the development of advanced manufactured devices and integrated systems.

110 FTE
Program Director: Gerry Wilson

Applied Physics
Includes capability based on Optical Science and Fabrication, Superconductivity, Hard Coating technology. (40FTE, Lindfield)

Agile Manufacturing
Capability based around Design, Prototyping, Open Access, Mechatronics, Electronics. (30FTE, Lindfield/Clayton)

Integrated Systems and Devices
Includes capability based on Nanophysics, Micro-Fluidics, Flexible Electronics. (40FTE, Clayton/Lindfield)
Cell Biology
Research concerning the structure, physiological properties, environmental interactions, replication, proliferation, and death of cells in the biomedical context, with a particular focus on stem cell biology. (35FTE, Clayton)

Biophysics
An interdisciplinary science using methods and theories from physics to study biological and molecular systems. Core competencies include the use of both experimental and theoretical tools to interrogate physical samples. These instruments and techniques are used to observe, determine, and model structures of, e.g., individual molecules, surfaces, cells, or nanostructures. (24FTE, Parkville/Clayton)

Biomedical Synthetic Chemistry
A capability concerned with molecular synthesis, including small molecules, polymers, bio-conjugates, and peptides with the intention of eliciting a biological response. Examples include medicinal chemistry, peptide chemistry, drug delivery systems, polymer-drug conjugates, biocompatible and bioactive polymers. (35FTE, Clayton)

Protein Science
Research on the structure, function, and biochemical significance of proteins, their role in molecular and cell biology, and their regulation and mechanisms of action. In particular, using bioscience skills to engineer the appropriate vectors in order to produce proteins of interest, either on a laboratory or large scale. Includes protein and antibody engineering, protein purification, fermentation. (31FTE, Parkville/Clayton)
CSIRO Strong Track Record in Metals Innovation

## HPMI

- **Manufacturing & Manipulation technology for novel Ti powder**
- **World’s first heel bone implant was 3D printed by HPMI**

### Products & Technologies

- **Cold spray technology – seamless pipes in fewer steps**
- **Intellisphere® real-time sensor (for pH, conductivity, etc.)**
- **Titanium powder-to-wire**
- **ArcWeld® simulation software**
- **Bulk metallic glass sheet**
- **Low friction plasma coatings for the Olympic cycling team**
- **Thermally assisted machining**
- **T-Mag® permanent mould casting**
- **CASTvac® vacuum valve for high pressure die casting**
Laser Assisted Machining

Nazmul Alam
Team Leader, Surfaces & Ceramics

Clayton Laboratory, 2016
Principles

Potential to increase cutting rate exists if tool face bearing load is reduced.

In-situ localised heating will reduce:

- Tool-chip bear loads, and
- Strength of workpiece

![Diagram of laser beam used in machining process](image-url)
• 4 kW cw diode laser system
• Wide rectangular beam (23 and 45 mm) integrated into laser head
• Cutting cell consists of laser head fixed into a 3 axis CNC system
• Closed loop temperature sensing and control system
• Time activated operation and data recording
Hardness Traverse

- Straight and shallow HAZ
- Confirmed by HV
- No residual HAZ left after machining
Milling Operation

Reduction of cutting force in LAM

Closed loop temperature control
## Typical Parameters

<table>
<thead>
<tr>
<th>Feed speed, mm/min</th>
<th>RPM</th>
<th>Cutter speed, m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>714.29</td>
<td>44.88</td>
</tr>
<tr>
<td>900</td>
<td>3214.29</td>
<td>201.96</td>
</tr>
<tr>
<td>1000</td>
<td>3571.43</td>
<td>224.40</td>
</tr>
<tr>
<td>1100</td>
<td>3928.57</td>
<td>246.84</td>
</tr>
</tbody>
</table>

Data in the yellow field are typical values used in conventional milling. Data in the green field are values used in TAM process.
## Quantifiable Benefits

<table>
<thead>
<tr>
<th>Example Component</th>
<th>Unit</th>
<th>Conventional</th>
<th>TAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of raw material</td>
<td>cm³ / (in³)</td>
<td>10,407 (635)</td>
<td></td>
</tr>
<tr>
<td>Volume of finish component</td>
<td>cm³ / (in³)</td>
<td>541 (33)</td>
<td></td>
</tr>
<tr>
<td>Material to remove</td>
<td>cm³ / (in³)</td>
<td>9,866 (602)</td>
<td></td>
</tr>
<tr>
<td>Roughing cycle time</td>
<td>minutes</td>
<td>822</td>
<td>130</td>
</tr>
</tbody>
</table>
LAM offers 5 times the cutting speed of conventional machining

With laser preheat the cutting force (2 mm deep cut) decreased by 20-30% in milling of Ti6Al4V

Up to 80% reduction in cycle time

Dry machining and only requires chilled air

Tool life is under investigation

Integration of laser motion in multi-directional cut is under investigation
Computational Design of Aerospace Coatings: A multi-scale modelling approach

Computational design project aims to increase experimental impact by:

- Reducing R&D development time and cost;
- Guiding experiments towards higher success paths;
- Providing effective data integration and knowledge sharing.

Feedback loops: Computational design software integration with an existing laboratory R&D program
Applications:

• Exotic aerospace material systems and composites;
• Design new materials on the molecular scale, and predict changes to service life;
• Accelerate material discovery through *in silico* modelling and discovery;
• Any global system with quantifiable multi-scale phenomenon;
• Estimate the effective service life-time and performance of batteries in realistic conditions.
Comp. Design Software Framework

Systems delivered to:

- **BOEING** – Life of inhibited paint films in service conditions;
- **BAE systems** – Life of protective films on aircraft exterior;
- **Australian Construction Industry** – Life of buildings and bridges throughout Australia;
- **Australian Galvanizing Industry** – Life of metal components on buildings in Australia;
- **Abu Dhabi Electrical authorise** – Life of Infrastructure in Emirate of Abu Dhabi.
Cold spray additive manufacturing is a solid-state additive manufacturing process capable of producing titanium billet, pipe and shaped 3D forms directly from a powder feed stock.
Advantages of Cold Spray

**Intellectual Property developed at CSIRO utilises low-cost powders as input materials for Cold Spray AM, thus decreasing the cost of manufacturing titanium billet and bulk 3D shape pre-forms.**

- HDH, GA, PM sponge or novel titanium powder can be cold sprayed
- Solid state deposition – no melting, therefore no solidification defects
- No vacuum required for oxygen sensitive materials such as titanium
- The powder deposition efficiency is very high, above 95% in most cases
- Cost effective – lower capital and operating costs
Nanostructured Thin Films Materials

- Inorganic hard & corrosion resistant coatings
- Antifouling Diamond-like carbon (DLC) coating
- Carbon-based protective coating
- Bio-interface Layer
- Transparent Conducting Oxides
- Thin Film Glassy Metal
- Inorganic Catalytic Nanoparticles
Our Capabilities

Our key technologies in the fabrication of nanostructures and thin films can be separated into the following categories:

- Magnetron sputtering
- Plasma activated CVD
- Filtered cathodic arc deposition
- Nanoparticle Generator

**Filtered Cathodic Arc Deposition System (Hard & Nanocomposites Coatings)**

**Multi-Layer Magnetron Sputtering Deposition (DC, RF and Reactive)**

**Transfer Arc Nanoparticle Generator**

**Plasma Activated Chemical Vapour Deposition of Diamond-Like Carbon**
Industrial Scale Deposition Facility

Dual Chambers
Cryopumped $10^{-6}$ mbar
1 m diameter
Computer controlled
Substrate Rotation
Linear Ion Gun 450 mm
Potential roll to roll capability
To assist the manufacturing industry to grow and prosper through innovation by providing them access to advanced manufacturing tools in a collaborative environment.


Concept Laser Cusing M2 for steels, Al, Ti, Ni, CoCr. Powder bed. Low surface roughness.

Plasma Giken PCS-1000 cold spray for solid state deposition of Al, Cu, Ni, Ti, Ag, Zn, Zr, etc.

Optomec LENS MR-7 blown powder machine for Ti, Ni, steels, Al, etc. Composite material possible.

Voxeljet sand 3D printer to print sand moulds with complex geometries.
CSIRO powder manipulation technology (PMT) converts low cost metal powders into high value feedstock suitable for additive manufacturing techniques such as cold spray and powder bed systems.
PMT - Reducing the cost of metal feedstock

Ti Sponge $15/kg

CSRO PMT $50/kg

GA Powder $250-400/kg

Final Product

~$65/kg

>$265/kg
CSIRO has the capability to produce 45 kg/hr of product via cold spray.
Financial proof of concept

Using a low cost metal powder for billet manufacture is a highly cost effective and efficient manufacturing route

One 45 kg/hr cold spray system:

- **Fixed Capital** = $3.2m
- **Depreciation** = $2/kg billet produced
- **Utilities** = $2/kg billet produced
- **Fixed charges** = $4/kg billet produced
- **Total product cost** = $8/kg billet + materials
High throughput materials facility
Use of High Throughput materials techniques for a variety of materials challenges:

- **Chemspeed Robot**
  - MOFs for gas storage
  - Nanoparticle drug delivery agents
  - Ophthalmic polymers
  - Catalysts

- **HT Synchrotron Characterisation**
  - Iron oxide nanoparticles
  - MOFs for gas separation
  - Liquid crystal MRI contrast agents
  - Ionic Liquids
  - Nanoporous silicates and titanates
  - Nanoporous battery materials
  - Composite clay-polymer materials
HT XRD analysis platform capable of analysing 30 samples/hour, requiring <10 mg sample.
Multivariate Analysis

Principal Component Analysis

> 3000 reactions
~1000 meso-scaled patterns

400 screened using synchrotron PD
~200 have large unit cells indicating porosity of MOFs

Normalised patterns

Raw patterns

RESULT3, X-expl: 81%, 81%

crystalline

amorphous
Flexible Electronics Facilities & Equipment

Discovery → Device testing → Scale-up

Large-scale trials

Materials Discovery

Materials Characterization

Device Fabrication

Device Testing

Prototype Development

IPE Stream

TFSC Stream

Device testing

Discovery

Scale-up

Large-scale trials
Multi-fibre Processing R&D Facility
**Production capability**
- recombinant proteins for in-vitro and animal trials (100mg to g quantities)
- large quantities (kgs) for biotransformation, soil remediation, etc. experiments
- process development and optimisation

**Microbial capacity**
- 10x bench-top reactors
- 5x 15L reactors
- 2x 20L reactors
- 1x 50L reactor
- 1x 100L reactor
- 1x 500L reactor
- cell homogeniser
- large-scale TFF system
- various chromatography systems

**Tissue culture capacity**
- 3x Bioflo™ bioreactors
- 4x 25L disposable systems
- 1x 150L stirred tank reactor
- various QC systems
Proven capabilities

- largest ‘open’ facility in Australia
- **ISO9001 accredited** (upgradable to cGMP if needed)
- platform technology provider (internally & externally)
- transient and stable protein expression
- state-of-the-art equipment and laboratory design
- pilot scale for full process development
- seamless process transfer to CMOs
- backed up by other CSIRO expertise
- deep collaboration with Australian and overseas companies
Capabilities

- Production of proteins and cells (mg to kg quantities)
- Optimisation and process development
- Seamless transfer to commercial partners
A few selected projects

- large-scale monoclonal antibody production for PATH (Gates foundation)
- animal vaccine development work for CEVA (European company)
- protein production for human Phase-I clinical trial for a US company
- antigen production for animal trials Spirogene (Perth)
- monoclonal antibody production against Hendra virus
Monash University - Monash Centre for Electron Microscopy
University of Melbourne - Materials Characterisation and Fabrication Platform
Deakin University - Institute for Frontier Materials
La Trobe University - Centre for Materials Surface Science
Swinburne University of Technology - ANFF Biointerface Engineering Hub
RMIT University - Micro Nano Research Facility
CSIRO - CSIRO Manufacturing Flagship
Artificial leaves enhance light-to-chemical energy conversion

Left: SEM image of the top view of a fabricated artificial leaf (light harvesting structures), where the white bar corresponds to a length of 200 nm. Right: Diagram illustrating the artificial leaves and the size scales involved. Credit: D. Gomez
A BRIGHT IDEA -> 20 years -> product
CSIRO megatrends
Shaping Australia’s future in the world

1. MORE FROM LESS
Innovation in meeting human needs by more efficient use of mineral, water, energy and food resources in light of escalating demand and constrained supply.

2. PLANETARY PUSHBACK
Changes in earth systems from the global to microbial are creating challenges for humanity including climate change and antibiotic resistance.

3. THE SILK HIGHWAY
Rapid growth of emerging economies and the transition from industrialisation into technologically advanced service sectors.

4. FOREVER YOUNG
The rise on the ageing population, retirement savings gap, lifespans, healthcare expenditure, diet & lifestyle related illness and mental health awareness.

5. DIGITAL IMMERSION
The exponential growth in computing power, device connectivity, data volumes, internet users, artificial intelligence and technological capabilities.

6. POROUS BOUNDARIES
Changes in organisational models, governance systems and employer-employee relations in a more agile, networked and flexible economy which breaks through traditional boundaries.

7. GREAT EXPECTATIONS
The rise of the all important experience factor as society and consumers have rising expectation for personalised and positive experiences involving social interaction, morals & ethics and the physical world.
Independent Emergency Flooding System

- Underground infrastructure along bank of river
  - Permanent physical barriers that can rise
  - Superhydrophilic polymer swells to create an impermeable barrier
  - Intervention from emergency response possible but not essential
- Remote monitoring
  - Weather from satellite
  - Force sensors in bodies of water and above normal waterline
  - Sensing people and animals
  - Alarms and warnings

Safety systems to prevent injuries to nearby residents
Smart System for on-farm Manufacture of Agricultural Formulations

- Black container distributed to site containing all chemicals and automated formulation equipment
- Data input
- Algorithm calculating required formulation
- On demand, on-site mixing of adjusted chemical composition with locally sourced water
- Formulation stability no longer an issue
- No distributor overheads
- Weather from satellite
- On-board sensors
- Manufacture on demand
- Lowers requirement for training and expertise of farm staff
- No human error or handling of concentrated toxins
- Decreased amount of toxic material distributed on the ground
- Temperature
- Humidity
- Water hardness
- Water purity
- Aerial drone photographs
- Weed image analysis
Use Case: Advanced Robotic Embodiment

Problem: Long-term autonomy for robotics is a huge barrier to the pervasive adoption of robotics in myriad areas, and stock components are a limiting factor for many robotic applications and body types.

Solution: A new breed of actuators based on next-gen materials and inspired by biology to promote flexible, natural movement and interact more easily with the environment.

New Science

Combining autonomous science with advanced materials, sensing, processing, and control algorithms.

The automatic identification of suitable advanced materials, and construction of bespoke joints based on their required functionality.

Creating actuators based on biology — synthetic tendons and structural components for flexible movement.

Simple moving parts based on, e.g., Shape Memory Alloys and smart flexible plastics.

Redundant muscle bundles for energy reclamation and graceful degradation under component failure.

Energy management systems, efficiency, harvesting.

An internal “nervous system” for fault detection and control.

Generation of control algorithms that can exploit the strengths of the new actuators. Holistic integration of the above.

Eventually, the ability to construct entire robots for a specific task using specialised materials and highly optimised physical embodiments.

Key

- Project
- Business Unit
- Product
- Use Case

Flexible joints for navigating difficult environments

Simpler actuation with less mechanical failure for long-term deployments

Self-repair/assembly

Specialised robots, built on demand, uniquely designed to be the best at a given task.

The ability to perform missions that current robots cannot

Remote environmental monitoring

Disaster response

Autonomous Maintenance

Confined spaces

Extending lifespan of existing robots

Extreme environments

CSIRO
Proposed process from here

Longlist: Submissions to Futureact

Evaluation process within Futureact by the science council

10-15 Large Projects

20+ small activities

Shortlisted

MAY 13-18th
(before SICOM presentation)

MAY 18+19th
(before SICOM presentation)

2-day meeting by MATA61 council

Current evaluation questions

- Estimated investment level required
  What level of investment would you estimate would be required to do this project?
- Estimated return on investment of proposal
  What level of return on investment would you estimate would result from this project?
- Estimated science risk of proposal
  How risky do you estimate related science would be?
- Potential technology viability of proposal
  Do you think the technology required for this proposal is viable?
- Potential societal impact of proposal
  What level of societal impact would you anticipate would result from this project?
- Your rating of this proposals overall potential?
Proposed process from here

Following the successful award of platform...

Evaluation in Futureact of designed projects

MATA61 council to decide and select a portfolio of shortlisted systems or “test beds”

All ideas

Low cost
   High potential

High Risk
   High potential
Proposed process from here

Following the successful award of platform...

Shortlist: range in terms of size, scope and risk profile evaluating cumulative projections

Multidisciplinary Teams established ~ 10 people
Including:
- Project leader,
- Design consultant, Chemist/Materials Scientist, Process Engineer, Materials Informatics, Robotics, Autonomous Science

Full design process undertaken for each system
Where should our FSP investment be

Gartner Hype Curve: Not before the curve? Then not developed in FSP!

FSP wants to be before the technology trigger...
Overall process

1. Longlist of concepts
2. Brief concept, potential project objectives and forecast budget developed in Futureact
3. Evaluation by M.A.T.A.61 council
4. Shortlist of ~35 concept systems
5. Council decide on a portfolio of “systems” or test beds
6. Evaluation of designed systems in Futureact
7. Budget Estimations updated and Projections developed
8. Detailed design process for entire system
9. Multidisciplinary teams established
10. Systems fully designed
11. Components mapped to existing technology including the Gartner Hype curve
12. Specific Projects designed
13. New projects picked up from backlog as budget allows.
14. If reach IRL 3 then move to BU
15. Continuous monitoring by Council
16. Split into sub projects in Futureact
What does the vision look like?

- Long list of concept ideas
- Evaluation of concept ideas by M.A.T.A.61 Council
  - MAY 18-19th (before SICOM presentation)
  - Short list of selected concept ideas to be expanded into detailed system designs
  - Evaluation of concept ideas by M.A.T.A.61 Council
  - Selected systems & test beds to be fully designed

Project concepts with partners
Best ideas from Think Tank
Best ideas from Crowd Sourcing
Current FSP projects

Use Case: Advanced Robotic Embodiment

New Science

Estimated investment level required for proposal

Estimated return on investment of proposal

Potential technology viability of proposal

Potential societal impact of proposal

Your rating of this proposal's potential

Potential technology viability of proposal

Estimated return on investment of proposal

Potential societal impact of proposal

Your rating of this proposal's potential

Vision, governance and operation discussion document | Danielle Kennedy
**Proposal title**
4D printing designed using human genetic blueprint for personalised food

**Proposal description**
Combining genetically designed food with in home manufacturing or printing of food.

**Proposal category**
Food

**Project proposal on Venn diagram**
- Materials
- Processing
- Sensors
- Autonomous science
- Informatics
- Robotics

**Estimated investment level required for proposal**
What level of investment would you estimate would be required to do this project?

Minimum: 0 1 2 3 4 5 6 7 8 9 10 Major

**Estimated return on investment of proposal**
What level of return on investment would you estimate would result from this project?

Low: 0 1 2 3 4 5 6 7 8 9 10 High

**Estimated science risk of proposal**
How risky do you estimate related science would be?

Low: 0 1 2 3 4 5 6 7 8 9 10 High

**Potential technology viability of proposal**
Do you think the technology required for this proposal is viable?

Low: 0 1 2 3 4 5 6 7 8 9 10 High

**Potential societal impact of proposal**
What level of societal impact would you anticipate would result from this project?

Low: 0 1 2 3 4 5 6 7 8 9 10 High

**Your rating of this proposal’s overall potential**

Low: 0 1 2 3 4 5 6 7 8 9 10 High

Any other feedback / comments / clarifications on project proposal:
Estimated return on investment is a drawback on this proposal.
Autonomous crop feedback and management

**SCORE SUMMARY**

| Item | Average | aaron.foote@csiro.au | affected
|------|---------|----------------------|-----------
| Autonomous crop feedback and management | 6.78 |
| Please complete your evaluation (Edit pencil, Save draft, Submit final version) (1.0) | 6.78 |
| [No Category] (1.0) | 6.78 |
| Estimated investment level required for proposal (3.0) | 6.33 |
| Estimated return on investment of proposal (2.0) | 6.33 |
| Estimated science risk of proposal (2.0) | 6.87 |
| Potential technology viability of proposal (1.0) | 5.87 |
| Potential societal impact of proposal (1.0) | 5.80 |
| Your rating of this proposal’s overall potential (1.0) | 5.67 |

**SCORE COMPARISONS**

- Estimated investment level...
- Estimated return on invest...
- Potential technology viabili...
- Potential societal impact...

**PIPELINE**

- Show All Projects
- Show All Projects

**GATE DECISION**

- Show All Projects
- Show All Projects

**GATE RESPONSES**

- Project
- Average User Score

- Potential technology viability of proposal (0.14)
- Estimated science risk of proposal (0.14)
- Estimated return on investment (0.14)
- Estimated investment level (0.14)

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Pipeline of Projects Managed continuously

Aim for projects to be moved to BU at the latest when they move into RL3.

Proposal portal open all year round

Proposals moved through workflow at monthly council meetings.

Projects accepted when budget available
Our Cheerleaders!
Thank you