CAPACITY TEN-SEVEN

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FES S/P2/00467/00/00/REP
DTI/Pub URN 06/689

Contractor

ICP Solar Technologies UK Ltd

The work described in this report was carried out under contract as part of the New and Renewable Energy Programme, managed by Future Energy Solutions (FES) on behalf of the Department of Trade and Industry. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of FES or the Department of Trade and Industry.

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CAPACITY TEN-SEVEN

SUMMARY

Project Capacity Ten-Seven sought to bring together leading UK industrial expertise in the required disciplines to “define the parameters for the design of a new solar cell process plant with a capacity about 10MWp per annum and establish the optimum substrate size, cell configuration and junction structure and include the necessary research to confirm that these key characteristics are suited to high volume low cost production. “

The nominal 3 year programme was progressed from January 2002 to August 2005, though with a 1 year suspension due to the liquidation in December 2002 of the Lead Contractor, Intersolar / British Photovoltaics Limited (BPL). Despite the reduction in actual project work timescale to 30 months, the project successfully achieved all its goals, being completed under the direction of ICP Solar UK Limited.

The key aim of the project was to determine an optimum ‘$/W’ solution for the plant design, using well developed and understood cell materials and structures. This differentiated the work from much other external developmental activity which sought to increase cell and panel efficiency through the use of new thin film materials and processes, often at the expense of production costs. Accordingly, a further target set for the project was that the Capacity Ten-Seven plant design should, in full production, be able to produce solar panel at a production cost target of less than $1 per peak watt.

The project objectives were addressed through six interrelated technical work Activities each with its own sub-objective and work plans. These were:
A. Fundamental studies
B. Front Contact Deposition
C. Semiconductor Deposition
D. Rear Contact Deposition
E. Cell Isolation
F. Initial Design Study.

The project technical work comprised a mixture of studies and reviews, primarily by ICP and Plasma Quest Limited (PQL) based on open literature review and discussions with relevant industry contacts;

practical work, primarily Exitech, PQL and West Technology Systems Limited (WTSL) for the development of the large area laser patterning and semiconductor deposition prototype plants to provide essential ‘proof of concept’ and / or risk reduction data for the project; and the definition of supporting Performance, Cost and Risk assessment tools used to rank the various process and system options within the overall plant design.

Although constrained by more limited equipment, time and facilities availability than originally anticipated, the Project work was concluded successfully to meet the Project goal of defining the Capacity Ten-Seven production plant outline design. The work showed that the project precept was correct, i.e. concentrating on optimising cell structure and plant design to achieve best overall production efficiency, as opposed to best photovoltaic (PV) conversion efficiency, could provide the basis for a highly cost competitive solar PV product.

The project has delivered all the required results to meet the overall project objective of defining the parameters for the design of a solar cell process plant with a capacity about 10MWp per annum. Cost studies show that for the preferred cell option and a number of equipment options, the production cost target of 1 $/Wp can be achieved for the standard large area (nominal 130cm by 66cm) glass based solar panels. This is less than half the cost of production of the current ICP plant.

As expected, the panel efficiency produced by the plant will not be comparable to that produced by the best rival technologies, but the cost advantage more than offsets this and is expected to result in the Capacity Ten-Seven products proving highly competitive for large area, low cost applications.

The plant design uses either well established technologies and processes or, in the case of the semiconductor deposition and laser patterning systems, uses new designs that have been developed and satisfactorily proven in this project. The plant therefore represents a low risk commercial proposition.

A number of minor technical choices and de-risking studies are recommended to be addressed whilst more detailed design is progressed, but in all cases the commercial risk is small as proven alternate options exist for the technical risks to be addressed within the overall project cost targets.

The project has therefore achieved its overall goal of positioning ICP Solar UK to proceed with detailed design of a Capacity Ten-Seven production facility that will meet with future expansion plans.

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1. INTRODUCTION

By 2001 the Intersolar Group's amorphous silicon solar photovoltaic (PV) panel manufacturing plant at Bridgend had, with DTI assistance, been improved to a capacity of 3MWp per annum from its initial 1MWp per annum design specification. However, with the solar PV market growing at 40% per annum, Intersolar expected to exceed the plants capacity within a 3-5 year timescale, possibly as early as the end of 2004. As such there was a clear need to have plans in place to increase capacity by that date.

Consideration of commercial options for achieving this led Intersolar to the conclusion that a further development of the existing and established amorphous silicon technology had the potential to achieve the required throughput and associated cost reduction targets, if certain key equipment and process developments could be achieved.

Accordingly, the Capacity Ten-Seven project was formulated to address these developments. The work built on the successes and recommendations of the prior Metamorphousis project. In addition, the existing Electra-Slate and Electra-Clad projects were also expected to feed directly into this program.

Initial estimates suggested that a solar conversion efficiency gain of around 40% might be realised from the combined projects, which would translate into a stabilised cell efficiency of 6-7%. When added to the cost reductions that underpinned the Capacity Ten-Seven development objectives, this would result in a highly competitive solar PV product. Initial projections suggested that the Capacity Ten-Seven plant should be able to produce large area, monolithically integrated solar PV panels at a cost below $1 per watt peak. This would enable the cells to be used in a wide range of electrical applications, particularly the high growth rooftop market.

A plant operating in this way was expected to remain viable to at least 2010, by which time one or more of the emerging new '3rd Generation' solar PV technologies should have reached a sufficient maturity to allow it's ready replacement or upgrade. In addition, it was anticipated that the initial products from the plant would require changing throughout the life of the plant and, as such, the project was required to focus on the most cost effective and potentially versatile solutions – i.e. a modular approach to the process was preferred to allow replacement or upgrade of individual solar panel process elements.

The following report describes the key work and results from this Capacity Ten-Seven project.

2. BACKGROUND

Background - Project

Despite an inherently lower solar conversion efficiency than most other solar cell types, amorphous silicon (a-Si) based thin film solar PV panels remain a major contender in the solar energy market due to their very low cost, leading to a low '$/W' cost (the cost of the panel per peak Watt (Wp) i.e. power output in full sun). The cost of thin film solar cells is also highly volume dependent because of this relatively lower direct cost; higher levels of throughput spread the fixed costs over more panels, reducing the cost of each. In the mid 1990s, Intersolar Limited developed a new high rate deposition process with support from the SPUR programme. At the time of the Capacity Ten-Seven projects initial proposal, this had been implemented and proved over several years, increasing the capacity of the Bridgend plant from its initial design1MWp p.a. to 3MWp pa.

Encouraged by this success and the results coming from the subsequent DTI supported Metamorphousis project (which was nearing completion), Intersolar proposed a new project to address a programme of research to resolve the technical issues inherent in planning for the next production plant at a capacity level of the order of 10MWp per annum.

The new project – titled Capacity Ten-Seven – sought to bring together leading UK industrial expertise in the required disciplines to address the following objective:

"to define the parameters for the design of a new solar cell process plant with a capacity about 10MWp per annum and establish the optimum substrate size, cell configuration and junction structure and include the necessary research to confirm that these key characteristics are suited to high volume low cost production. "

The project had substantial overlap with other DTI assisted projects run by Intersolar, with mutual benefits to all. The Electra-Clad and Electra-Slate projects were addressing layer deposition, laser patterning and cell configuration issues relevant to the project. In return, the large scale, high throughput requirements for the Capacity Ten-Seven project were relevant to future production scale up studies and costing for these projects. In addition, the earlier Metamorphousis project had provided the necessary foundations for cell development and material options that would be required by the work, as well as having established a Trials Deposition Unit (TDU) for a-Si deposition that could be used in initial cell options studies.

This project was started in January 2002 by Intersolar Group and its collaborators – Plasma Quest Limited (PQL), Exitech Limited and West Technology Systems Limited (WTSL).

PQL bought specialist expertise in plasma deposition technology, specifically relating to 'thin film' silicon deposition using plasma enhanced chemical vapour deposition (PECVD) and rear contact deposition using sputtering technology, to the project. Exitech, the UK's leading laser technology company, had produced laser systems for the thin film solar and Thin Film Display industries and were ideally placed to develop the 'next generation' laser patterning system required by the proposed plant. WTSL bought expertise in the engineering of vacuum deposition equipment and had been involved in the upgrade of the plant at Bridgend and in producing the TDU under the Metamorphousis project.

Following the liquidation of the Intersolar Group in December 2002, the project was put on hold, pending reappraisal and replanning of the project by the new owners of the Intersolar Bridgend production plant, ICP. After nearly a one year delay, the project was approved to continue in October 2003 under the direction of ICP Solar UK Ltd, and using the same group of collaborators, with a revised completion date of July 2005. This allowed slightly less than the originally planned 3 years for the work, but recognized that, in many areas, the collaborators had continued to address some of the technical issues relevant to the project under other in-house projects. This was particularly the case for the Laser work, resulting in a far more developed and proven design by the project end than had been originally anticipated.

(It should be noted in the following that where ICP is referenced, this should be read as ICP and / or Intersolar – a majority of the staff and facilities transferred from Intersolar to ICP Solar UK, maintaining project continuity.)

Background - Technical

As stated above, the overall project objective was to define the parameters for the design of a new solar cell process plant with a capacity about 10MWp per annum, though within the broad constraint that the technologies used should be a progression of the current ICP plant or, where this was unrealistic, be based on widely established and proven alternatives.

Critically, it was agreed that the key aim of the project was to determine an optimum '$/W' solution for the plant design, using well developed and understood cell materials and structures. This differentiated the work from much other external developmental activity which sought to increase cell and panel efficiency through the use of new thin film materials and processes, often at the expense of production costs. It was ICP's belief, based on prior successes that the basic a-Si based production technology had yet to achieve its limit in production efficiency terms, even if the indications were that the solar conversion efficiency limit had been met. This approach would also remove the uncertainty and risk associated with attempting to base any large scale production on new and commercially unproven materials and systems.

Accordingly, a further target set for the project was that the Capacity Ten-Seven plant design should, in full production, be able to produce solar panel at a production cost target of less than $1 per peak watt. As such the equipment cost, material cost, throughput, labour cost and efficiency would all be key factors in achieving this, and it was ICP's expertise in these commercial factors that would provide the overall guidance to the project technical work.

The project objectives were addressed through six technical work Activities. These were as follows:

Activity (a) : Fundamental studies
This addressed the cell structures, layouts and technologies that were expected to be required to meet the probable range of products to be produced by the future plant.

Activity (b) : Front contact deposition
This work was to "define the requirement for the deposition of the transparent front contact film." It was to resolve issues regarding cost and quality that had arisen as a result of ICP experience with in-house Atmospheric Pressure Chemical Vapour Deposition (APCVD) coating in place of bought in product.

Activity (c) : Semiconductor deposition
The Semiconductor Deposition Activity was to address the full range of critical design and process issues that would need to be resolved to permit the Capacity Ten-Seven Plant semiconductor deposition system to be specified.

Activity (d) : Rear contact deposition
This was to review options for improved rear contact materials and processes that had potential for improving PV cell performance and to then conduct trials on the most promising options. It was intimately linked to cell structure development under Activity (c).

Activity (e) : Cell isolation
The objective of the Cell Isolation activity was to design and prove a new generation of advanced laser tools, capable of high throughput – at least 5 MW solar cell annual production per machine, where a machine operated either at the infrared wavelength for the Front Contact

patterning, or at visible ‘green’ wavelengths for the a-Si interconnect and Rear Contact patterning..

Activity (f) : Initial design study
This addressed the overall Capacity Ten-Seven plant and its operations. It took into account the probable range of products to be produced and the supporting infrastructure that would be needed by the major process tools that were to be separately defined via other Activities.

In practice it was found that the interdependence of activities a) Fundamental Studies and (f) Initial Design Study was so great as to require them to be combined at a technical level. Therefore these have been reported under a joint heading in the following sections.

The following technical report essentially sub divides the mandatory Work Performed, Results and Discussion report sections according to these work activities, largely but not totally reflecting the sub-division of work within the consortium. Where necessary, overall considerations are dealt with under the sub-section a) Fundamental Studies and Initial Design Study. Figures are similarly labelled to match this reporting scheme.

Finally, it is obvious that much of the work, in defining ICP’s future commercial plans and means of achieving same, is highly commercially sensitive. Accordingly, a majority of the detailed information used in or originating from the project is not included in this report, though so far as is possible the key information has been included in a ‘sanitised’ form. Those seeking further detail should contact ICP or the relevant collaborator(s).

3. WORK PERFORMED

In practice, the project technical work comprised three interdependent elements; these were:

A. Studies and reviews, primarily by ICP and PQL based on open literature review and discussions with relevant industry contacts, to define, detail and maintain the currency of the overall Capacity Ten-Seven plant design, products and operating methodology.

B. Practical work, primarily Exitech, PQL and WTSL for the development of the large area laser patterning and semiconductor deposition prototype plants, and associated trials for these and the rear contact Activity, designed to provide essential ‘proof of concept’ and / or risk reduction data for the project.

C. Initiation and definition of supporting Performance, Cost and Risk assessment tools by ICP and PQL that would be used to determine the optimum Capacity Ten-Seven plant solution(s) for the project and to identify those areas of technical risk that needed risk reduction studies within the project remit to allow the option to be considered[1].

In outline, the work progressed as a number of (overlapping) tasks, conducted chronologically as follows:

1. Initial studies and review of overall Capacity Ten-Seven plant options, as constrained by initial project definition.

2. Initial a-Si PECVD (semiconductor) deposition system development options appraisal.

3. Outline definition of the baseline Capacity Ten Seven Plant, including initial Outline Specifications for the critical Semiconductor Deposition, Sputter Deposition and Laser Patterning sub-systems.

4. Definition of the practical trials work and System Specifications for the Semiconductor Deposition and Laser Patterning prototypes to be developed within the project.

5. Detailed engineering definition and design of an a-Si PECVD system to meet the requirement for trials work within the project, concluding in a Final Design Review and approval to proceed with construction of a Large Area Chamber (LAC) and associated modifications to allow integration with the existing TDU.

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[1] Note that these were, for confidentiality reasons, maintained and further developed outside of the project and are therefore not delivered as part of this report. However, their initial development and their inputs to the project are reported as necessary.

6. Detailed engineering definition and design of the Laser Patterning Tool to meet the requirement for trials work within the project.

7. Definition and development of software tools to support the studies of optimum Capacity Ten-Seven plant options, to define risk areas and the work required to mitigate these risks (for promising options).

8. Trials work using existing plant and materials in order to address defined risks and / or to provide further data required for the ongoing optimum plant definition process (conducted outside of the project).

9. Build and commissioning of the Laser Patterning Tool prototype system.

10. Build and commissioning of the integrated LAC / TDU Semiconductor Deposition Tool prototype.

11. Trials work using the Laser Patterning and Semiconductor Deposition Tool prototypes, primarily in order to prove the design concepts and thereby address remaining risks in the optimum plant definition process.

12. Outline definition of the final optimum Capacity Ten-Seven plant options based on the above work, and identification of remaining trials and studies needed to resolve, mitigate, quantify or clarify remaining technical risks or uncertainties.

13. Outline definition of the required Capacity Ten-Seven plant infrastructure and additional systems required to support the already defined critical systems. Determination of those systems requiring further definition.

14. Final trials and / or studies. Final plant equipment definition and Outline Specifications as required.

15. Overall assessment of the project results and definition of the optimum solution for a Capacity Ten-Seven plant producing optimum value (i.e. $/Wp) solar PV panel products.

It should also be recognised that throughout the project, processes relevant to the project were being further developed and optimised at the ICP Bridgend solar PV panel production plant. The results of this process development were available to the project team throughout the work and provided substantial additional input to the work.

As earlier discussed, the project managed the work via a number of contractually discrete Activities, though the organisational and staff overlap on these ensured that the 'holistic' viewpoint so essential to the development of an optimum plant solution was maintained. To maintain consistency with the contracted work, these Activities provide the sub-sections for the report.

Work Performed – Activities a) Fundamental Studies and f) Initial Design Study

In outline, the work for this Activity was progressed in the following stages:

a). Initial review and assessment of cell and panel design options, definition of plant required to support these options.
b). Options review and prioritisation, leading to definition of Initial Outline Plant Design, Outline Specifications for major production items (Semiconductor Deposition, Laser, contact Coaters), trials requirements.
c). Periodic update of the plant design options in response to project trials work, systems development and external literature.
d). Plant infrastructure definition studies (last 6 months of project)
e). Final definition of Capacity Ten-Seven preferred plant options and Final Outline Plant Design (with supporting more detailed designs for the Semiconductor Deposition and Laser Patterning Tools).

Stage a) was primarily a paper and software exercise, involving substantial literature review, discussions with relevant plant manufacture and industrial users, supplemented in many cases by first hand experience of similar systems and processes. PV cell and panel options were an explicit and critical deciding factor in determining the production strategy and were also addressed at this time through literature review and discussions with solar panel manufacturers.

An initial 'sift' of the wide range of options identified eliminated those that were insufficiently developed or unproven in commercial production (or in some cases were found to be failing to deliver the results promised by published research results). The remaining options were subjected to cost of production studies to determine which provided the most promising solutions for further consideration within the project. These were supplemented by performance and risk analyses, the latter especially focussing on the technical risk posed by some of the newer technologies.

Assessment of the results of this phase of the work for stage b) confirmed the initial project strategy: the main challenges were in the semiconductor deposition and laser patterning tools and would require substantial trials and systems development within the project. The front and back contact processes also needed consideration (supplemented by more limited trials). Finally it was confirmed that the 'secondary' plant systems and infrastructure – e.g. transfer systems, wash systems, storage – although widely available as Commercial Off The Shelf (COTS) items, would require outline definition towards the end of the project to ensure compatibility and throughput consistency with the primary systems as defined by that time. I.e. it was essential to the cost optimisation objective that the plant design was developed and completed as an integrated whole.

The stage b) options review also gave rise to trials that were required separately from systems and process development. These were primarily relevant to the cell design element of the work, and were a series of 'risk reduction' or production assessment trials to be addressed under Activity c) Semiconductor Deposition (reported later).

To deal with the rapidly growing and in many cases interdependent options developing under this Activity, a formal Performance, Cost and Risk (PCR) matrix was also developed for use on the project. This allowed project trials and research priorities to be more readily identified. Although initially developed for project use, it was decided that the contents of this PCR matrix – especially the cost and performance factors – represented important and commercially sensitive intellectual property (IP) and the PCR analyses were therefore progressed externally to the project.

From this point project activity became primarily focussed on progressing the critical systems development and the supporting trials defined at stage b). Low key activity continued however on revising and refining the overall plant design and cell options, eliminating those that proved unfeasible or clearly too costly or unnecessary as more data was obtained. This stage c). of the activity also maintained a watch on relevant external developments.

By the beginning of January 2005, the work on defining cell and critical or major systems and process options was sufficiently progressed to allow the remaining infrastructure of the Capacity Ten-Seven plant to be defined. Stage (d) initially reviewed and reported on the overall requirements, as a result of which a number of infrastructure elements were defined as requiring more detailed consideration and analysis. This was completed and reported at the same time as the final definitions of the critical and major systems and processes were finalised, allowing completion of the work through definition of the Final Outline Plant Design (and supporting subsystem definitions) in stage e). Of this Activity.

Work Performed – Activity b) Front Contact Deposition

Initially it was expected that new APVD systems would be able to readily overcome the cost and quality issues previously experienced in ICP and the initial focus of the work was on assessment of suitable plant for in-house use. However, it was recognised that the combined and increasing markets for large area solar and display panels were providing the suppliers of pre-coated glass with a substantial incentive to optimise costs, quality and user customisation of their product, to a degree that might well erode any cost differential and therefore the scope of work included assessment of various bought-in product.

The front contact for the standard Capacity Ten-Seven product (glass panel based PV) was defined to be a transparent conductive oxide (TCO) that was compatible with later processing, in particular a-Si cell deposition at up to 250 deg.C. The standard TCO used in ICP production was tin oxide, usually textured to improve PV panel performance through light scattering[2]. This readily met the requirement.

In amorphous silicon based single or multi-junction solar modules, the textured TCO coating is an integral part of the active solar cell and has three critical functions:

(i) It acts as the front electrical contact to the PV cell.
(ii) It transmits light into the solar module, and
(iii) It scatters the incoming light to increase the 'effective absorption length' in the photovoltaically active part of the solar module.

These three functions require the tin oxide coating to have properties unique to thin film solar cell applications. Moreover, the subsequent processing steps are "tuned" to the particular surface features of the tin oxide coating and therefore reproducibility of characteristics, including texture, is critical.

Prior production at the Bridgend factory had used both bought in supplies of pre-coated glass (i.e. with a suitable TCO already deposited) and in-house coated glass panel; a number of alternate suppliers had been tried for the former, though at the start of the project the products of Libbey-Owens-Ford (LOF) were preferred.

During the course of the project, our technology watch also identified a development in an alternate materials technology, zinc oxide (ZnO) that required consideration.

Thus, three options were considered for the front contact:

i). Continued purchase of the current commercial products, either 'off the shelf' or custom made, which was textured tin oxide (SnO_2) coated glass.
ii). Purchase of the equipment required for in-house production of tin oxide coating on glass.
iii). Changeover to ZnO coated glass, a system for the deposition of which had recently been reported to have been achieved, and which appeared to provide improved PV response.

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[2] Note that the level of texturing required is dependent upon the later cell structure and generally requires customisation to achieve optimum PV performance.

The four major issues considered in this Activity were security of supply, cost, performance and process maturity (i.e. the level of risk associated with adopting the technology for a new start commercial plant).

The work largely comprised discussions and on-site meetings with the relevant suppliers, supported by in-house assessment of their products using both the Haze and Transmission measurement system acquired for the project and deposition trials where relevant. The results of this work are reported later.

Work Performed – Activity c) Semiconductor Deposition

This work was planned to be a mix of paper studies, practical trials and experimentation. Paper studies included technology and process options review and cost modelling within the overall plant performance, cost and risk assessment work. The trials were to be conducted using the previously developed TDU, initially fitted with a standard 'Bridgend' deposition chamber and plate holder set, later the new LAC constructed for the project. Activities to be covered were:

1. Number of junctions: whether single or stacked cells were optimal in terms of performance, stability, application and cost.
2. Layer materials: the extent to which micro or nano-crystalline layers or parts of layers could be used to enhance the above parameters.
3. Deposition Techniques: these were to be minor variations on PECVD only, though with the realisation that a 'watching brief' needed to be kept on external developments that might render this well established technology redundant.
4. Chamber and holder set design: to optimise the stability, uniformity, performance, gas utilisation and throughput capability.

There were a number of constraints applicable to this task, resulting from earlier considerations of the required upgrade path and initial technology definition work for the Project. These were:
1. The LAC would be a PECVD system for the deposition of a-Si based thin film solar cells[3].
2. The LAC would be a batch load system, to produce 48 off nominal 125x66cm plates in a 3 hour deposition cycle (load to unload)[4].
3. The LAC would make use of the established removable 'plate holder set' system to permit variation in substrate load (for alternate products) without alteration to the system.

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[3] I.e. the basis of the Capacity Ten-Seven Project was to optimise plant for the existing, well established technology in use by the Lead Collaborator, as it was expected that this would provide the best '$/W', low risk solution.

[4] Separate assessment of continuous feed 'in-line' systems showed them to be a high capital cost, potentially low reliability option, with no clear benefit over an optimally designed batch load system.

Essentially therefore the technology to be developed and the LAC itself were cost and performance optimised developments of the existing a-Si based technology in use by ICP. It was on the basis of the above that the Semiconductor Deposition work plans were detailed.

In outline, initial planning envisaged the following, essentially sequential activity:

1. LAC definition and design, including associated TDU software and hardware modifications required to support the work objectives.
2. Start of LAC build.
3. Review of deposition technology and process options, input to overall plant performance, cost and risk assessment. Determination of optimum scheme(s), key drivers and any uncertainties requiring resolution through trials.
4. Initial trials of critical elements using the unmodified TDU.
5. Installation and commissioning of new LAC and associated modifications
6. Trials using the LAC to resolve remaining issues, primarily resulting from technology scale up.

At this point, the project objectives would be achieved. Additional 'stretch' targets were also informally set to provide further 'de-risking' of the likely plant design, and to gain valuable advance process experience with the new larger PV plate

7. Deposition (and associated fabrication) of PIN[5] based solar panel to proposed Capacity Ten-Seven plant definition.
8. Deposition of promising variant structures and materials as full size solar panel – these variant structures would be those assessed as unsuited to initial production due to technology or process complexity / immaturity (and hence consequent high risk for initial commercial operations), but which nevertheless held out promise of delivering significant benefit if correctly realised.

Notwithstanding the one year suspension of the project following the initial Prime Contractor's liquidation, compounded by severe delays to LAC delivery and commissioning, this plan was essentially followed, the only significant change being that most of the 'deposition issues resolution' was conducted using the unmodified TDU. However, the anticipated development of the Bridgend factory facilities intended to support the project work was seriously delayed – or in the case of the expected back contact coater upgrade, did not take place. This severely curtailed activity on stretch activities 7 and 8, though it did not impede progress on the project's essential activities 1 to 6.

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[5] I.e. cells made using the well established a-Si p-layer (P), i-layer (I), n-layer (N) junction structure, whether single or multi-junction – e.g. a PIN-PIN cell.

The activities were recognised as being highly interdependent, necessitating continual technical management and redirection as the work progressed and difficulties emerged and were resolved. The following sections of the report therefore deal with work and progress under three main headings: the LAC design, build, commission and development (activities 1, 2, 5, 6 above); the testing and definition of the preferred cell and materials options (activities 3, 4 and 6 above); and the progress made on the LAC stretch targets – solar panel production - (activities 7 and 8 above).

Work Performed – LAC Development

The LAC was the critical path item in the above work, and it was essential that design and definition work was started immediately in the Project. For this reason, the initial LAC requirements definition took into account the need to provide for the most demanding process under consideration for the Capacity Ten-Seven project – a dual junction cell structure using multiple material types to optimise solar PV performance, i.e. the system was designed to provide more capability than might be required once the options had been more fully considered and costed. Additionally, the requirements definition also included features that resulted from experience with the existing Bridgend deposition systems – e.g. a simpler and more robust RF connection.

Taking these requirements and the overall Project requirements and restrictions into account, engineering studies commenced from the Project start, focussing on issues that might arise as a result of the size scale up required[6]. By April 2002, initial cost and options studies had defined a starting basis for the a-Si deposition system and a full Requirements Specification was produced to permit detailed design work to begin.

In outline, the primary function of the LAC was to provide a system in which the process changes arising from increasing the plate size could be addressed, in particular gas flow and RF uniformity issues. The unit was also to allow testing of a number of potential process and operational improvements that had arisen with operations experience, both with the ICP factory production units and with the TDU. These required a degree of adaptability to be built into the system, and the capability to be able to return to 'tried and tested' methods as a failsafe.

The unit was required to provide batch processing of 125cm x 66cm x 3mm thick glass plate contained in removable 'holder sets' (HS), as with the ICP factory systems. Total glass load would be 48 plates, in 6 HS. The LAC would need to vacuum compatible (i.e. ultimate pressure better than

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[6] The existing chambers at Intersolar were designed for 8 off nominal 92x33cm plates – i.e. the new chamber would take 16 times the material of the old chambers, with commensurate size, weight, vacuum engineering and process support implications, regardless of design detail.

10^{-6} mbar at room temperature) and capable of operation at 250 degrees Centigrade.

Detailed engineering design supplemented by regular design meetings and formal Design Reviews was largely completed by late 2002. Following Project suspension, the design was completed, reviewed and accepted by all collaborators at a Final Design Review held in November 2003. After final detailed design changes, costing and ICP/PQL approval of West Technology’s final designs, build of the unit and acquisition of supporting infrastructure and components was committed to in early 2004.

Build commenced immediately, essentially unaltered from the original plan but with longer lead times for delivery due to resource reductions and re-allocation within the consortium. During the build period, the existing TDU was partially allocated to trials aimed at ‘de-risking’ some elements of the design, particularly those relevant to process gas feed and vacuum extract distribution and improvements to the Radio Frequency (RF) power input to the system and therefore plate deposition uniformity. These trials proved the viability of the LAC design, eliminating the need to implement some contingency options in manufacture.

The LAC was delivered for installation late that year and was finally debugged and completed acceptance testing in December 2004. A general view of the new LAC and originally chambered TDU is shown in Figure C.1.

Cell performance measurements, in conjunction with observations and measurement of thickness and material non-uniformities on panel produced by the LAC, identified a number of key modifications required to improve LAC performance. The resulting gas delivery and vacuum extract system modifications were implemented in early February 2005, completing the build and optimisation phase of the LAC work activity.

Subsequently, the LAC met all the specified requirements and, as a result of the Project suspension and delivery delay, was also able to benefit from a number of software improvements and the greater process experience developed on the unmodified TDU in that time. Accordingly, rapid progress was made in commissioning the system. From this point on, the major thrust of the work in the LAC was to determine the process conditions and configuration required to provide the basis of a full production facility, though this also resulted in further development of the LAC design as the more exacting testing uncovered further improvements that could be made.

The commissioning work established the full functionality of the TDU / LAC combination, including all software and hardware upgrades of the

TDU required to account for the wider range of processes to be supported in the LAC. The LAC was therefore capable in principle of depositing single cell based panel to the established ICP process recipes and with the same resultant panel efficiency. In practice, there were several design aspects that were expected to need optimisation to achieve this performance; these were:

1). Adjustment of process gas inlet distribution, to ensure an even process gas supply to the individual plate positions.
2). Adjustment of the vacuum extract distribution to achieve, in conjunction with 1), a uniform process gas flow and pressure over the plate positions.
3). Optimisation of gas flow in conjunction with 1 and 2 above, to avoid depletion effects (and resultant quality and thickness non-uniformity of deposited materials).
4) Analysis of operation of and (if required) modification to the innovative RF power connection scheme to ensure reliable, noise free power input to the LAC plate carrier electrodes.
5). Optimisation of RF power levels, in conjunction with 3 above, to achieve a uniform, high quality materials deposition process.
6). Establishing the thermal profile of the chamber heaters and system 'wait' times to achieve required plate process temperatures.
7). Overall process vacuum optimisation, particularly of the new high vacuum pumping stages, to minimise the impact of materials cross contamination and residual vacuum impurities. This was a particularly critical aspect, as the LAC volume and – when fully loaded – materials surface area was many times greater than that of prior ICP systems.

In addition, the need to process smaller plate sizes than those intended for eventual production by the LAC, in order to allow use of existing ICP patterning and metallisation facilities, required additional trials to confirm the equivalence of using several smaller plates to occupy the position intended for a single larger plate. I.e. it was important to establish that the boundaries (and small inter-plate gaps) of the smaller plates did not introduce significant RF power, gas flow or temperature non-uniformity.

Essentially there were four 'stages' to the work performed on the revised LAC/TDU system, though in practice there was substantial overlap on each – and on occasion repetition of earlier stages – as the system configuration and processes were developed to produce the final PV panels. The four stages were:
1. Determine configuration / process conditions to achieve visually uniform deposition.
2. Determine process conditions to produce good quality a-Si layers (P, I, N)
3. Produce and optimise conditions to achieve good performance single junction solar PV panels.

4. Produce and optimise conditions to achieve good performance dual junction solar PV panels.

Configuration changes were limited to minor engineering change, e.g. addition of gas flow and vacuum extract baffles to even out precursor gas distribution, revision of RF grounding to improve power coupling to RF plates. Process changes focussed initially on the primary conditions of gas flow, process pressure and temperature, and RF power. For stages 3 and 4, process modifications were primarily layer deposition time and RF power, supplemented by limited work on interlayer aspects – e.g. use of high vacuum clean up, addition of very thin interlayers. These aspects of the work are considered more fully in the later Results and Discussions sections.

Work Performed – Preferred Cell and Material Options

Initially, literature review supplemented by discussions within the a-Si solar cell community provided the major input to this activity.

At an early stage in the work it was apparent that, despite significant R&D reports of multiple junction and multi-material structures achieving higher stabilized solar conversion efficiencies than standard a-Si based single junction structures, the cost-benefit when considered solely in the context of the deposition process was marginal at best. The essential considerations were:

1. A dual junction structure allowed the use of thinner I layers in the cell, reducing the impact of light induced Staebler-Wronski (S-W) degradation of the material electronic quality – i.e. a more stable cell was possible.
2. A dual junction cell also allowed the use of alternate bandgap[7] materials, e.g. a-Si:C for the front cell, to optimize light absorption in the two stacked cells and, in principle deliver a more efficient solar cell.
3. A triple junction cell was feasible, using narrow bandgap a-Si:Ge to further increase efficiency and, potentially, stability.
4. Each additional junction required substantial increases in process time within a batch system[8] due to the need for long inter-junction pump out times between cells to eliminate deleterious cross contamination of dopant gases.
5. The use of Germane gas to produce a-Si:Ge for a triple junction cell would additionally greatly increase the cost of cell deposition.
6. The a-Si solar panel commercial community was undecided as to the benefits of single versus dual junction (and triple junction was little used). Those producing single junction based cells were considering (or in the process of changing over to) dual junction, whilst at least one other dual junction manufacturer was seriously considering reverting to single junction in order to improve costs and yield.

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[7] Strictly this is a 'mobility gap' in a-Si based materials and is only analogous to the bandgap present in crystalline materials in terms of its effect.

[8] Or substantial additional capital equipment for in-line systems.

From a deposition process perspective, it therefore appeared that dual and triple junction technologies would only be really beneficial if the intended product required higher efficiency, e.g. where there might be a space or weight limitation. This was not the market segment that the Capacity Ten-Seven Project was considering. Accordingly, triple junction cells were clearly inappropriate (excessive process time and cost), whilst dual junction could only be considered if production costs could be constrained to near those of single junction.

However, within the full Capacity Ten-Seven plant design assessment (reported earlier), dual junction technology was shown to yield substantial overall capital and process cost reductions. For this reason, the dual junction cell was determined to be the technology of choice for the Capacity Ten-Seven work.

However, if dual junction technology were to be implemented, then a number of uncertainties needed to be resolved - and the ability to succeed within certain constraints proven. In addition, there were a large number of potential material and detailed cell structure improvements that had been identified as having potential for improving solar panel performance and which required practical testing to define their value. A programme of work was therefore undertaken in the (unmodified) TDU to address these issues.

Within the scope and resources of this part of the project, particularly the need to integrate with 'de-risking' trials for the LAC, it was recognized that only a sub-set of the identified possibilities could be realistically addressed. The programme of work was therefore defined to address the most critical aspect of dual junction production as a priority, with material and cell design elements restricted to those most likely to impact the dual junction structure. Accordingly, the TDU trials work was planned as follows:

1. Determine the feasibility of producing a simple dual junction cell using the ICP baseline processes, i.e. with the same gases and layer compositions. By definition, this precluded using a wide bandgap material for the first junction.
2. If successful, determine whether this can be produced within the 3 hour 'turn-around' time required for realistic production and / or the modifications that will be required to permit this. Ensure that these modifications are included in the LAC for later testing.
3. Determine the impact on dual junction cell performance of using additional thin interlayers, interfacial treatments (e.g. hydrogen plasma treatment) and specialist pump/gas purge 'clean up' processes at the critical n-p interface between the two junctions.
4. Determine whether the processes can be adapted to deposit a-Si:C based layers for use in the dual junction cell, both as an alternate to the standard ICP 'p layer window' material and to allow use of a 'tailored' wider bandgap first junction to improve cell performance. (Note that the

standard ICP materials processes do not provide a capability for the required wider bandgap undoped layers.)
5. Determine whether the processes can be adapted to produce narrower bandgap nano or microcrystalline based materials for use in the second junction (to absorb more of the longer wavelength ‘red’ light).
6. Based on the results of the above, determine the optimum dual junction that can be accommodated within the 3 hour process target and run trials to optimize the structure.

All of the above trials sets 1 to 5 were completed within the available timeframe prior to LAC delivery (at which time the TDU became unavailable). Dual junction optimisation (trial set 6) was only able to progress sufficiently to demonstrate the viability of the technology in the TDU, but the best panel performance results are not believed to represent the final optimum.

From this point on, project work focused on the LAC, initially installation and baseline process optimisation, later solar cell and panel fabrication. The aim of this work was to prove the LAC as a production tool using already proven cell designs and accordingly no further cell and materials options studies were performed.

Work Performed – Solar Panel Production

Following achievement of the primary project goals with the LAC, work continued towards meeting the stretch targets discussed earlier. Due to limited time available, and in view of the results obtained earlier using the unmodified TDU to investigate alternate materials (see later Results), work was limited to the following:

- Produce and optimise conditions to achieve good performance single junction solar PV panels based on ICP standard process.
- Produce and optimise conditions to achieve good performance dual junction solar PV panels based on ICP standard process.

The changes to the project resulting from the liquidation of Intersolar effectively removed the possibility of fabricating full size panels for testing, as the (non-project) facilities expansion at the Bridgend plant, assumed in planning to provide ‘free issue’ resources for the project, did not occur as planned.

A contingency processing scheme was formulated in June 2004, but in the event could not be implemented in full, as it was only late in the project that the required sized laser patterning facilities were installed at ICP Bridgend, and the anticipated large area coater was never acquired. Thus the PV panel activity had to make use of multiple 'standard ICP production' width (33cm) panels cut to 66cm length in place of individual 125x66cm Capacity Ten-Seven plates, with pre and post processing managed as best possible within the ICP fabrication line when time was available to accommodate the special changes required.

This scheme proved operationally difficult and resulted in significant trials failures. In addition, access to ICP laser patterning and metallisation proved more difficult than anticipated due to high production utilisation at his time. As such, a majority of the cell testing was performed on small area devices of 1cm^2 taken from full size (125x66cm) plate. This had had the benefit of providing immediate post deposition junction assessment independent of other fabrication effects that might detrimentally affect performance. However, the more limited panel fabrication and assessment that was conducted confirmed the equivalence of SAD measured performance and full panel performance.

The detail of the processes used and engineering changes required to fine tune the LAC/TDU to produce good quality PV panel are highly confidential and are therefore only reported in general terms in the Results and Discussions sections.

Work Performed – Activity d) Rear Contact Deposition

The work for this topic essentially mainly comprised two interdependent studies. The first was the experimental trials of the most promising and most readily achievable 'low-risk' – i.e. production proven – rear contact material schemes. The second study was a review of relevant coating technologies, starting with selection of the most promising candidates for inclusion in the overall Capacity Ten-Seven process review and, after completion of the rear contact trials, assessment of these candidates and selection of the optimum solution.

An additional minor study was also addressed by the work. It was clear early in the work that the sputter deposition process was scoring more highly over evaporative processes on the basis of assumed, rather than proven, performance factors. It was therefore decided to undertake some limited trials work to ensure that these assumptions were well founded, through a short Rear Contact Process Trials study.

For clarity, these topics are reported separately below.

Work Performed - Rear Contact Materials Trials

The primary function of the rear contact (in a monolithically integrated glass panel based module) is to provide a robust, efficient and effective electrical contact to contact the cell N layer of the cell, to interconnect cells by making contact to the underlying front contact (usually a TCO – transparent conducting oxide) at regions where the a-Si material has been removed and to provide a connection point for external wiring. The material must be able to be readily and cheaply deposited in thin film form over large area substrates, and must possess good step coverage properties, low stress and good environmental stability. These requirements are readily met by a wide range of metals, all of which have been extensively researched and developed for the semiconductor industry.

A secondary function is to reflect any light not absorbed in the first pass through the cell in order to provide a further opportunity for absorption and electrical carrier generation. It is this aspect on which the majority of research into rear contact materials for thin film solar PV is focussed, and the substantial external research effort, both academic and industrial, has yielded a number a candidate options for future use.

Aluminium is the most widely used material for the rear contact in current generation thin film a-Si:H based solar cells and forms the usual 'baseline' for improvement for a-Si based solar R&D. Aluminium fully meets the primary electrical contact function and production requirements, especially the need for low cost and plentiful supply, and has adequate reflectivity for the secondary function. Current favoured alternate materials systems include the use of a silver for improved reflectance (with or without further layers to improve interface properties or lower the production cost), and zinc oxide (ZnO) as a diffusion barrier / reflection enhancer[9]. Other workers have investigated the texturing of the rear contact using ZnO/silver in order to optimise the reflectivity and scatter to obtain best performance.

In all cases it must be borne in mind that much of the R&D work is directed at getting the best possible cell efficiency, not necessarily the most cost effective cell. In view of the variation in results reported by some workers and our own experiences with the optimisation of multi-layer materials systems onto essentially reactive materials (i.e. the a-Si:H surface), first hand experience is essential in determining the overall balance of benefits and costs.

The delay in the project resulting from the loss of Intersolar at the end of 2002 had an unplanned benefit in that PQL had acquired additional sputter deposition facilities in the meantime that could be made available to the project. This allowed the scope and magnitude of the work to be greatly extended from the initial plans.

The trials addressed the following proven material and process options:
1. Standard evaporated aluminium (baseline performance of current ICP cells).

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[9] Most recently the use of LPCVD deposited ZnO (i.e. transparent) in conjunction with a white paint diffuser has been reported. However, the exact impact of this is uncertain from the report and the work is beyond the scope of the trials. However, this technology will be the subject of further investigation for the remainder of the project.

2. Sputtered aluminium (baseline Capacity Ten-Seven production choice).
3. Silver (to test impact of improved reflectivity); thin silver with aluminium overlayer if successful (material cost reduction trial).
4. The use of thin oxides (especially ZnO) as an intermediate layer for the above systems, in particular to form the ZnO-aluminium multi-layer system that is widely used by other workers.

The trials were conducted on single cell and tandem (dual junction) structures, the impact on the latter being of especial interest in view of the desirability of enhancing the rear cell absorption as much as possible to provide scope for dual junction re-optimisation. Additionally, a variety of alternate materials were used to help determine the degree to which the reflectivity properties of the material (as assessed from measurement of the individual thin film on glass) were relevant to the impact of the film when deposited onto and potentially allowed to react with the a-Si cell.

The sputter system used was of PQL proprietary design, equipped with a multiple sputter target and reactive sputtering capability. This permitted the deposition of multi-layer rear contacts – including oxide interlayers – without breaking vacuum.

Evaporated aluminium, to provide comparative data with trial rear contacts, was produced using a PQL electron beam evaporator. The equivalence of cells produced with evaporated rear contacts at ICP by hot wire filament and at PQL by electron beam evaporation had been confirmed by work in the prior 6 months.

Trial cells were produced as ‘Small Area Devices’, single cells of 1cm^2 area, in order to eliminate any detrimental effects due to poor interconnect processing. It was accepted that further work to check interconnect capability of the most promising multi-layer candidates would be required; in the event, this was not necessary.

Work Performed - Coating Technology Selection
This work was primarily a paper exercise, requiring current literature review to supplement the substantial existing knowledge and experience within the consortium, combined with a critical analysis of the Capacity Ten-Seven requirements.

The ICP process used thin-film aluminium deposited by hot wire filament evaporators, providing an adequate, low capital cost solution to their production panel requirements. However, this technology had been surpassed by highly developed commercial in-line coaters that provided better material quality and step coverage, and were capable of processing the far larger panel sizes required for the Capacity Ten-Seven plant design.

An initial review of suitable, proven commercial deposition technologies identified the following broad technology options:
1. Physical Vapour Deposition (PVD) based technologies, i.e. 'flash' evaporation and sputtering of metals and transparent conductors.
2. 'Screen printing' of thick metal conductors (i.e. from suitable precursor 'inks').
3. Chemical Vapour Deposition (CVD) technology for zinc oxide (transparent conductor) overlain with a white 'backscatter' material.

The latter technology had been only recently developed and had demonstrated a potential for significant performance gains over conventional metal rear contacts, due to the improved scattering of light. The deposition technique was announced as 'commercially available' only in the last 6 months of the Project and it was not possible to gain access to such plant to independently evaluate the material. In addition, we were advised by those researching the technology that there were remaining processing issues associated with achieving the required zinc oxide layer texture and patterning, and with washing / cleaning the layer. Accordingly, the technology was not further considered, though it was recommended that a watch be kept on this technique for the future.

Screen printing technology was developing rapidly, primarily driven by a desire for low temperature, low cost patterned metallisation of flexible (plastic) materials for various consumer goods market and very large area flat screen displays. At the time the materials and techniques were unproven for the reliable and long term formation of the intimate ohmic contact required to the semiconductor silicon and the technique was therefore assessed as inappropriate for consideration as part of the Capacity Ten Seven plant definition. However, as before, it was recommended that a watch be kept on this technique for the future, especially with regard to the possibility of using it to add on the end cell thick connector strips prior to encapsulation.

It was anticipated that the rear contact trials would favour a multi-layer materials system, immediately eliminating the batch load upgrade of the ICP systems as a contender. As reported later, this proved not to be the case and the conclusion was that, at this time, the PV efficiency benefit of changing the materials system used for the rear contact was questionable. Accordingly, deposition system final selection was assessed as needing to be based on the production based considerations of throughput, cost and yield. In addition, the desirability to ensure that the system was sufficiently flexible to allow for future materials change and/or the use of proven multi-layer rear contact schemes was taken into account.

Thus the project rear contact technology final review primarily considered the choice of PVD techniques, with the deposition of aluminium – the basic rear contact material – as the priority requirement.

Both sputter deposition and evaporation techniques were well proven in this regard. The outcome of this review is reported in the Results section.

Work Performed - Rear Contact Process Trials

In-line sputter deposition technology was identified at the start of the project as also potentially resolving some production issues originating from the use of the batch 'flash evaporation' process. In particular, these were:

- line of sight coating limitations
- limited capability to modify process to optimise deposited material quality
- potential for interfacial contamination
- physical size requirement (and commensurate pump system increase)

The 'line of sight' coating provided by the axial filament source was not ideal for coating the laser patterned steps at the amorphous silicon and front contact scribe lines. Earlier investigation had shown that some production yield loss could be ascribed to breaks in the rear contact metal continuity at the most 'shadowed' scribes at the panel edges (see figure D.1). Whilst subsequent process development and panel layout design had largely overcome this problem for the current 33cm wide production panels, it was clear that the new 66cm wide Capacity Ten-Seven panels would be far more prone to this problem[10]. Sputter coating was a proven technology for achieving good conformal coverage to overcome this issue, and the plate feed arrangements within an in-line unit would also aid achieving the required uniformity and step coverage.

The evaporation technique also provided very limited scope to adjust process (within a given geometry). The vacuum pressure (affecting impurity content) and the evaporation rate were all that can be readily changed, i.e. without altering system build and geometry. In comparison, sputtering processes allowed more scope for 'tuning' the process to achieve the desired results – e.g. raising process pressure (not vacuum pressure) to introduce more 'scatter' into the material arriving at the substrate to improve step coverage or alter stress in the film.

The remaining issues with the ICP 'flash evaporation' process were primarily a result of running the evaporative process in a 'single shot' batch mode – necessitated by the use of the hot filament technique. Alternate continuous evaporation sources (e.g. electron beam) would allow ready inclusion of shutters (to avoid interfacial contamination) and continuous throughput. However, at this level, the evaporative technique became significantly more costly, comparable to the equivalent sputter system, whilst bringing none of the advantages.

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[10] In principle, the evaporation chamber could be 'scaled up' to double current diameter to maintain the same 'line of sight' angles for the new panel. However, this would quadruple the chamber volume (not allowing for increase panel length) and accordingly significantly increase the capital and running costs.

The decision was therefore taken early in the project to focus on the in-line sputter technique as the 'baseline' for the Capacity Ten-Seven plant. Whilst perceived as a low risk decision, this mandated some trials as a further risk reduction exercise. In particular, the expected improvement in rear contact material quality (i.e. density and internal stress, potentially improved interfacial adhesion) was expected to increase the difficulty of laser patterning the material.

Original plans had assumed that Intersolar would have a large area sputter deposition system available for the final year of the project; this did not happen. However, PQL were able to make use of a new development system at their premises to provide a suitably sized 'test vehicle' to address these sputtering concerns. Although more advanced in terms of capability and deposited materials quality than conventional sputtering, the PQL system was deemed suitable as a 'worst case' trial – i.e. the rear contact films deposited would have better adhesion, lower stress and be more densified than conventionally sputtered equivalents and therefore more difficult to process. The required laser patterning was performed at ICP using both the older BPL laser systems and newly acquired, higher accuracy current production systems.

Work Performed – Activity e) Cell Isolation

Work on this topic was limited to laser patterning and interconnection of the layers. The ability to rapidly and accurately laser pattern the three thin film layers making up the solar cell structure was a critical factor in successfully achieving the performance and cost balance required by the Capacity Ten-Seven plant design. Though the required laser tools were expensive to acquire and maintain, they were a far more cost effective technique than any alternate patterning schemes used in production, especially for very large panels.

The laser techniques required to process the a-Si and typical contacts layers were, in the main, well established. Standard laser processing tools for a-Si solar panels on glass substrates used infra-red solid-state lasers for the front contact (TCO film) insulation scribe and green solid-state lasers for the a-Si interconnect scribe. The final rear contact (thin metal film) scribe could also be performed with the green laser. Laser scribing all three lines had the advantages of closer line spacing (leading to improved solar panel efficiency) and lower production costs in a correctly optimised system. It should be noted that at the start of the project Intersolar had no experience of laser scribing the rear contact and that proving trials of this aspect of production were a critical initial element of the work.

Initial work produced the required specifications for both the laser process and Laser System. Briefly, the laser operations were specified as:

Scribe 1: consisted of laser scribing with an infrared laser the TCO insulation lines of the solar cell, and the complete removal of the TCO in 2 bands at the short sides of each panel.
Scribe 2: consisted of the laser processing (with a green laser) of interconnect holes in the a-Si layer.
Scribe 3: consisted of the scribing of isolation lines in the top metal layer, with the same green laser.
Scribe 4: consisted of a final isolation scribe of 2 mm wide around all four edges of the panel, removing all TCO, silicon and metal. This was done with the 1064 nm wavelength laser.

Figure E.1 shows a typical cross-section through a standard glass based panel resulting from this scheme in order to elucidate the monolithic integration achieved by the sequence.

In addition, trials were specified for alternate patterning and interconnect options that had the potential to reduce both capital and process costs. These were to provide the basis for future plant development (i.e. not the initial design) and are accordingly not reported in detail.

In the first year of the Activity, laser process tests were conducted on the various films to ensure full understanding of the optimum process conditions in terms of laser wavelength, spot size, fluence, pulse repetition rate, pulse length and side of beam incidence. These results confirmed that an IR laser was optimum for scribing the TCO (scribe 1) and deletion of the full film stack (scribe 4) with the beam incident from the coated side of the panel, whereas a green laser was preferable for a-Si and metal scribing with the beam incident on the film through the glass (scribes 2 and 3). Process parameters were established and proven that met or exceeded all the laser patterning goals, thus remaining work was able to focus solely on the design issues of plate handling, throughput and tool cost.

Initial design studies to meet the project Outline Laser Requirements for the laser tool led to a design based on vertically orientated panels using advanced new technologies of scanners, aperture projection and floating optics heads. A prototype handling jig was constructed to prove the design and, following design development, trials showed the design to be sound and effective, fully meeting the project objectives.

Original planning for the project anticipated a need for a design iteration following initial laser tool prototype production and testing. However, as a result of the one year project suspension, Exitech had independently developed and proven some of the design elements required by the Capacity Ten-Seven tool for other applications, primarily the thin film display industry. Thus the initially designed and fabricated prototype system proved to be fully effective in practice, requiring no further design iteration.

However, although technically successful, it was felt in Exitech that a lower complexity and hence lower cost solution could be achieved if the Outline Laser Requirements were relaxed to allow horizontal processing of the solar plates. Following review of the implications of this, it was agreed that this should be addressed as the Design Iteration task. A new design study was therefore undertaken to simplify the tool architecture and reduce cost.

A cost analysis of the first design showed that the high cost items in the earlier design were mostly associated with the mechanisms used to hold and transport the plates vertically. Hence the new design concentrated on creating a tool with horizontal sheet architecture with much simpler sheet handing mechanisms.

As before, trials of the new system have demonstrated that, with the allowed exception of vertical processing, the second design iteration fully meets the Capacity Ten-Seven project requirements for the Cell Isolation tool.

Thus the work under this Activity was concluded with two proven options for achieving Cell Isolation. The impact of this on the overall Capacity Ten-Seven plant design is considered in later sections.

4. RESULTS

Overall, the project has delivered all the required results to meet the project objectives. The designed plant uses either well established technologies and processes or, in the case of the semiconductor deposition and laser patterning systems, uses new designs that have been developed and satisfactorily proven in this project.

The following section reports the results achieved for each Activity. A significant proportion of the results have been simplified in the following to protect the project IP.

Results – Activities a) Fundamental Studies and f) Initial Design Study

The PV cell and supporting production requirements studies resulted in the definition of a 'baseline' Capacity Ten Seven plant suited to the production of the most prospective cell structure and materials options that had been identified for the project. In outline, the plant design adopted a mixture of in-line (i.e. sequential single panel processing) and batch processing systems – the latter primarily to keep capital costs low for the semiconductor deposition systems. This is shown schematically in Figure A.1.

The plant outline comprised a number of linked production sub-systems, with provision for automatically moving the substrate panel from one to the next and with appropriate storage and protection between modules. A number of options were retained in the process scheme, to allow for both changing product type and for other decisions to be made under this project, including proving the technical feasibility of some process steps and systems to be developed.

It was proposed that panel be moved through process in a vertical orientation, resting on the longest dimension side for ease of handling and compatibility with the preferred a-Si deposition and sputter coating systems orientation. As discussed under Activity e), this resulted in some additional complexity and costs for the laser patterning systems and, accordingly, some translation of orientation to the horizontal is present in the final design (for laser patterning and initial glass cutting).

In general, semiconductor clean conditions (i.e. class 1,000 or better) were not expected to be required during processing, though an overall reasonable level of cleanliness in the plant was considered desirable. However, some steps were identified as particularly prone to potential yield loss due to dust and debris and, if at all possible, clean (class 1,000 or better) transfer and handling conditions were recommended for these (indicated as 'Clean Process' in figure A.1).

The process systems were expected to be a mix of 'in-line' units – the laser patterning, cleaning and sputter deposition systems – and 'batch' a-Si deposition systems (and associated pre-heat ovens, post deposition cooling and storage modules). Plate storage prior to and post a-Si deposition was therefore necessary to match the in-line systems throughput (though it was considered possible to use the pre-heat and post-cool modules for this). The use of 'buffer' storage at other key transfer steps of the process also needed to be considered in order to accommodate temporary short-term hold-ups in the in-line systems (e.g. for laser system recalibration or adjustment or whilst a single system was being maintained).

It was considered essential that, wherever possible, automated measurement systems be included at key points in the production flow. The proposed minimum requirement is indicated in figure A.1. It was anticipated that this testing would be on a 'sampling' basis and non-destructive so as to allow tested panel to be returned to the production flow. An ideal system would be integrated into the production line; testing was anticipated to be very fast in comparison to normal sub-system throughput and, in principle, could be applied to all plate.

It was also confirmed that, ideally, all plate would be given a final performance test at the end of production, both to permit plate 'grading' and to assist in process monitoring. This test should ideally be a full 'power quadrant' I-V characteristic measurement under simulated AM1.5 illumination. It was expected that additional more detailed testing, including light soaking, would be performed routinely on samples and/or low grade or failed product. A test routine schematic had been previously defined under the Metamorphousis Project and was adopted as a baseline template for the later Test Infrastructure design.

The underpinning capital cost study, supplemented by initial estimates of production costs, confirmed that a plant made to this design could in principle achieve both the required 10MWp annual throughput and meet the 1 $/Wp production cost target. Accordingly, the required systems developments, options trials and other process development work to prove the validity of the design were progressed (as separately reported). Subsequent cost analysis using all the results from these activities has subsequently confirmed achievement of these throughput and production cost targets with the Final Outline Design for the Capacity Ten-Seven plant.

As anticipated, much of the plant infrastructure and equipment required to support the major deposition and patterning equipments proved to be readily commercially available. A first review of these elements concluded that the majority of the infrastructure required for the Capacity Ten-Seven plant was of low risk and had little impact on the plant design – i.e. the required systems were readily available, already proven in production and of insufficient cost impact to warrant detailed consideration within the project.

A number of infrastructure elements identified as needing more consideration in this initial review were gas handling and abatement, where current evaluations of COTS systems within the project had raised concerns regarding performance, reliability or safety. The report also identified a number of elements that require decisions to be made as to production methodology.

These were all considered in a further and final review. Specifications were obtained for Commercial off the Shelf (COTS) solutions for the previously undefined key systems and assessed as meeting the Capacity Ten-Seven plant requirements. These were automated wash facility, inter process plate handling and transport, buffer storage and automated solar I-V tester. Other systems and design changes were put on hold, as the optimum solution was seen to depend largely on final a-Si deposition chamber detailed design, safety and waste disposal legislation and the relevant COTS systems available at the time of final plant design. These were the a-Si deposition system plate load / unload interface, the hazardous gas abatement strategy and the gas panel re-engineering.

A critical finding of this work package was that reasonably priced COTS systems were already available for re-orientating glass plate (coated or uncoated) from the vertical orientation to horizontal and vice versa (e.g. as shown in Figure A.2). It had been assumed in initial plant definitions that one or other orientation would need to be used throughout the plant; these systems removed that constraint, with benefit to the Cell Isolation Activity (as reported in relevant sections).

Results – Activity b) Front Contact Deposition

Three major issues were addressed in the study. They were:

1. Security of supply
2. Cost
3. Performance

Only the tin oxide and zinc oxide materials as providing a suitable option for commercial front contact production. For the three options considered, the assessment for the above issues was:

Commercial product – i.e. glass panel already coated with a TCO (tin oxide) layer suitable for use in the manufacture of PV panel.
Security of supply – low risk (many supplier options, growing market)
Cost factor[11] - 0.87

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[11] The Cost Factor is unit area cost (in £) of coated glass panel after allowing for all processing, cutting and wastage.

Performance – as per current product, i.e. ‘standard’.

Note that, in general, all materials supplied for test met their physical specifications and were able to be used successfully to produce good quality solar PV panel. The exceptions tended to be from new suppliers offering much lower cost product; accordingly these were discounted from the results.

New APCVD plant (tin oxide)
Security of supply – medium risk (initially, falling to low as experience gained).
Cost factor - 0.71
Performance – lower than standard.

Again trials using materials supplied by the equipment manufacturers proved suitable for solar PV use. The results achieved from the test batches showed that the performance from test plate was 14W as compared to 16W for the procured glass. However, it was felt that, once tuned for the cell design, the performance would meet the quality of the commercially procured glass.

However a major performance concern was the reproducibility of the coating. The variations in sheet resistance, optical transmission and in haze all directly affect the performance of the solar module. The risk of having a wider distribution in performance (watts/module) would have negative financial consequences. Colour banding was seen on all samples from the various manufacturers. The negative consequence of this on solar modules was mainly aesthetic, but very important to customers for roof-top and architectural applications. Accordingly, this option was given an overall lower ‘performance’ mark.

Zinc Oxide products
Security of supply – high risk (new technology with current processing uncertainties)
Cost factor – not yet quantifiable
Performance – higher than standard (but unproven in production at this time)

The primary performance advantage of the zinc oxide system derived from improved transparency, which promised to deliver a 10% increase in PV cell performance when fully optimised – i.e. this was the theoretical improvement. This was potentially of significant benefit for panel manufacture, more so when considering overall PV installed costs.

In addition, recent reports had shown further PV enhancement through using the zinc oxide as a rear contact material, overlain with a white diffuse reflector (paint). If the promise of improvements from both front and rear contacts based on a single material process could be realised commercially, then this would be a significant development.

Overall, the performance differential was assessed to be positive for the zinc oxide option – possibly a performance gain of 15% in PV output. However, the immaturity of the technology and in particular the need to develop reliable production processes for the complete fabrication process made this a high risk assumption at this time.

Results – Activity c) Semiconductor Deposition

For clarity, the results for this task have again been separated into those relevant to the LAC Development, Preferred Cell and Materials Options, and Solar Panel Production.

Results: LAC Development – Design

The LAC tested a number of ideas for improving operations and / or reducing costs through design simplification. The following have been fully operationally tested and confirmed as suitable for incorporation into the production system with only minor detail revision.

1. Internal gas feed distribution.
2. Internal vacuum extract distribution.
3. Plate carrier design.
4. RF connection on loading plate carrier; this was designed to eliminate the need for manual RF connection (as on current ICP systems) and the occasional failures introduced by the 'flying lead' style of interconnect. Following recent internal design revision, these units have proved operationally sound.

Some aspects of the design have been shown to need some revision to fully achieve their potential and address the following specific results:

5. RF plate design; trials have shown that, at the process conditions required for good quality plate, this is an acceptable design. However, two issues arise: firstly, there is less 'tolerance' to process conditions, i.e. 'incorrect' or unsuitable process conditions can cause dust formation, requiring post deposition clean up; this might limit the scope of future improvements through use of alternate materials e.g. microcrystalline I layer[12]. Secondly, the design introduces a local deposition non-uniformity that has yet to be overcome; it is not clear at this time whether this is plasma or localised temperature non-uniformity induced effect.

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[12] This layer will require high power and high hydrogen dilution, significantly outside the range of current process testing.

6. The RF plates are a 'loose fit' in the plate carrier, to ease construction / maintenance. This has proved to be operationally imperfect (though manageable).

7. The plate carrier (holder set) design needs some modification to make plate loading easier and to relax glass cutting tolerances.

8. The limited physical and electrical contact provided between the chamber and the plate carrier by the chamber rollers, whilst greatly easing the plate carrier load/unload operation as intended, demonstrably fail to provide the required RF earth return. There are two aspects of the LAC design that need serious review and consideration for major redesign.

9. The access door will need to be replaced with a more ‘production friendly’ and robustly mounted unit.

10. Consideration should be given to leaving the (heavy) plate carriers in the chamber and loading / unloading glass from lightweight storage boxes or racks.

11. The LAC needs a heating system expansion to assist in achieving a more uniform thermal profile on the PV plate (see also 6 above).

It should be noted that there were no serious problems encountered with using the LAC as designed; the changes made throughout the project were mainly those anticipated in early planning and for which provision had been made in the LAC design.

The most severe problems resulted from the decision to minimise LAC cost and design risk, by limiting the LAC build to a single plate carrier positioned at one side of the chamber i.e. in the most difficult position to achieve uniform gas and temperature distribution. This required a number of internal trials specific modifications to ensure that the results achieved would be representative of the intended later fully furnished production systems.

In the event, it appears that these modifications have not been adequate to fully avoid gas distribution problems that would not occur in a fully furnished unit. Gas flows required to achieve good uniformity in the system have been higher than expected and limited experimentation suggests that this is due to escape of substantial gas to the unused chamber regions. If trials are to continue beyond the project, it is necessary that a full width/height aluminium or steel plate partition be installed in the LAC to fully isolate the single plate carrier position in use.

Additionally, only 2 heater plates – one either side of the plate carrier – were installed. Due to conduction losses to the unheated regions of the chamber, these have proven to be underpowered to ensure full temperature uniformity across the plate carrier, compromising plate performance. For any further work, it is recommended that an additional 2 heater plates be installed in the unused portion of the chamber – one on the outer wall, one close in to the partition recommended above.

Aside as reported above, all other elements of the LAC/TDU have performed as designed. Key amongst these are the RF custom 'minimum profile' matching units, designed to fit side by side under the LAC to allow them to be connected as close as possible to the RF plate connectors (thereby minimising potential RF loss and process variability). These units have performed faultlessly and proven remarkably rapid in there tuning response, which is now about 2 seconds compared to 10-15 seconds for the standard units in use at ICP. This is an important achievement for improving the timing of the thinnest layers of the PV cell – most critically the P layer, which is typically of short duration and in which 5 seconds 'tune-in' variability introduces substantial deposition time variability.

Equally, the higher power water cooled generators have proven reliable, with no overheat problems in even the hottest ambient conditions so far experienced (in excess of 30 degrees C room temperature and high humidity leading to condensation on and within water cooled items).

The PLC reprogramming to provide automated use of the high vacuum pump within the process (critical to optimising process time and performance of the dual junction cells) has proven totally effective. All vacuum checks, valve operation and high vacuum pump start / stop has been shown to operate faultlessly under full PLC control in response to entering a single pressure requirement 'code value' in the process menu. This allows use of this high vacuum capability at any stage of the process as required.

Results: LAC Development - Uniformity Trials

Initial trials were hindered by an erratic and unpredictable software problem that had not occurred during the earlier commissioning. West Technology was eventually able to isolate, identify and remedy this defect and the system has operated without problem since; the remedy has provided a far more rugged and reliable process that is now an integral part of the TDU/LAC design.

Loading and unloading of the LAC with the 33x66cm panels required to fit in with ICP processing proved difficult, but achievable. Deposition onto the multiple small plates was shown to be successful, with no problems or significant non-uniformities introduced by the plate boundaries.

As anticipated, initial trials showed severe deposition non-uniformity, as shown by Figure C.2. The dominant problem was severe powder generation over a band approximately centred on the plate or, at lower RF power levels, a central region of thicker deposition, falling off to the plate edges (Figure C.3). Investigative trials confirmed that the cause was primarily non-uniform gas feed, due to a minor design flaw in the LAC distribution system, combined with a lesser vacuum extract non-uniformity.

Engineering changes were implemented to resolve this and were effective in largely, though not completely, eliminating the problem (Figures C.4). Analysis of plate and process changes indicated that, although there were further improvements possible through minor gas inlet and vacuum extract upgrade (readily supported by the new configuration), the major problem was one of RF plasma non-uniformity.

Initially, poor RF performance was evident in the system, with high levels of reflected power and 'noisy' input levels. This was traced to severe cross-talk between the (two) RF generators due to unexpectedly inadequate RF shielding at the power inlets. Following build and installation of suitable shielding assemblies, RF performance improved dramatically to provide stable power levels with little noise or reflected power.

However, RF power level optimisation remained severely hindered by performance limitations on the nominal 300W output RF generators, which became unreliable due to overheating above 150W, even with substantial additional forced air cooling. Scaling the required power levels from current ICP systems indicated that a power level of 250 to 300W was required.

New 1.2kW power supplies were therefore acquired and fitted to the LAC during March 05. The opportunity was also taken at this time to further improve gas feed and vacuum extract distribution systems, and to improve the temperature uniformity in the chamber.

Following these LAC modifications, the more exacting uniformity demands for cell production, coupled with slight changes in process condition from those used before showed that the uniformity issue was complicated through strong interdependencies in the potential controlling variables – RF power, process pressure, and gas flows. As a result, a significant proportion of the available process development time was expended on this aspect of the work; this was essential to achieving the required deposition over the full panel size.

In summary, the following variables were found to impact uniformity as follows:
i). RF power: the standard ICP process already runs at very low plasma densities, requiring low RF power input. Due to variable input coupling losses, initial work with the LAC was compromised by effectively varying plasma density run to run. In uniformity terms, this was visible as a loss of deposition starting at the lower corners of the plates and, as power was further reduced, extending further up the short sides of the panel. The use of higher power to compensate this proved ineffective due to excessive 'dust' generation in the plasma (when coupling was good), which led to the formation of powdery deposits on the plate surfaces. Ultimately, improvement to the RF earth return scheme and more robustly close coupling the RF match units to the LAC proved effective in eliminating the coupling variability, allowing optimisation of the RF power level and virtual elimination of RF induced edge non-uniformity.

ii). Temperature profile: variably, a top to bottom non-uniformity was evident in many process trial sequences. Material at the upper part of the plate was of good quality, material at the lower part was of very poor quality – no more than a powdery deposit in many cases. Initial attempts to eliminate this incorrectly focussed on gas flow and pressure. Ultimately, it was determined that the operational methodology being used was introducing significant temperature variation between the top and bottom of the plate, due to convection effects within the incompletely heated chamber during the atmospheric pressure overnight heat up of the plates. The impact of this was governed by ambient temperature conditions, hence the apparent variability – i.e. good samples were produced during the hottest weather when chamber 'cooling' was minimum, though even in this case testing with an optical pyrometer showed the bottom of the plate to be 50 degrees C cooler than the top, an unacceptable difference for good uniform cell performance across the plate.

Ultimately, this non-uniformity issue was largely overcome through running the overnight plate heating in the LAC under vacuum, though it is suspected that some residual edge and corner non-uniformities still result from the incomplete LAC heater fit – i.e. plate positions closest to the unheated LAC walls still show non-uniformity.

iii). Process pressure and gas flow: this was the final – and most difficult – of the non-uniformity sources to identify and control. It is now understood that the process pressure measurement (by Barocell gauge), although taken at a point in close proximity to the plate carrier edge and with line of sight to the space between the plates does not provide a good measurement of the effective pressure within the plates. As the latter is strongly dependent on the gas flow, an increase in this requires a compensating decrease in process pressure set-point to otherwise maintain prior process conditions and allow the impact of gas flow to be separately assessed. Failure to provide this compensating pressure set-point change impacts the uniformity through changes to the plasma uniformity resulting from the changed inter-plate pressure and therefore the RF power distribution.

With the above issues resolved (as fully as the LAC will currently permit), good plate uniformity has been achieved, adequate for solar cell trials. Figure C.5 shows the near perfect visual plate uniformity obtained at the end of the project.

Results: LAC Development - layer deposition process development

Initial work with the LAC used process parameters that were 'scaled up' from those earlier used in the standard chamber TDU. Within the bounds of the uniformity issues reported above, these were found to provide an adequate start point for cell fabrication trials. Due to the delays in the trials resulting from resolving the non-uniformity issues, it was therefore decided to omit individual layer deposition process optimisation as a separate element of the work and progress immediately to single junction trials.

The achievement of a working, even low efficiency, solar cell junction is a far more exacting test of materials quality than any separate single materials layer testing, and many successful PV cells had resulted from the extended uniformity trials. Essentially, these confirmed that intrinsic material quality was good, that the required doping to both P and N conditions could be achieved, and that there were no interlayer problems resulting from layer deposition start up or termination effects (e.g. surface oxidation). As a result, there are no separate results for this stage of the work.

Results: LAC Development – solar cell deposition

In a similar manner, within the limits of the previously reported uniformity issues, initial small area cell performance provided a reasonable start point for optimisation and no further LAC modifications or development was required to particularly address this part of the work.

Results of the cell deposition work in the LAC are reported later in this report section.

Results: Preferred Cell and Materials Options

The extensive open literature available, coupled with first hand in-house expertise in prior dual junction development, allowed first basic tandem junction cells[13] based on standard ICP layer technology and of reasonable (4%) solar conversion efficiency to be achieved early in this part of the work.

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[13] I.e. First and second cells of same materials – this is not generally considered an optimum design, ideally the first cell is of wider bandgap material than the second.

However, raising the conversion efficiency to that of the single panel cells proved more difficult than expected, with a degree of inconsistency in the results making process trends difficult to extract from the performance data. These issues were ultimately resolved through the use of small area (1cm^2) devices (SAD); these simple structures could be fabricated on-site at PQL (i.e. co-located with the TDU) eliminating the variables introduced by off-site laser patterning, metallisation and inter-site transportation. Process optimisation, in conjunction with ICP fabrication enhancements to meet the more exacting needs of the dual junction structures, then yielded significantly improved performance, with final dual junction based panels achieving near equivalent performance to the single junction panel[14].

Following this, work proceeded on assessing the impact of inter-layer surface treatments or the inclusion of additional thin a-Si based layers, primarily at the inter-junction n-p 'recombination' interface. In general, little impact was observed. However, the addition of a very thin, highly p doped a-Si:H layer at the n-p interface did prove beneficial, significantly increasing Voc and fill factor, to provide a dual junction based solar panel of equivalent (16W+) performance to the single junction cells produced in the TDU. Figure C.6 shows the measured solar performance characteristics for an optimum dual junction based solar panel deposited using ICP 'standard' layer processes and this additional layer.

An important aspect of this achievement was that this performance was achieved using processes that could readily be run at the existing ICP plant – i.e. the deposition process represented the lowest risk option for later plant development. More critically, deposition optimisation studies were run at the same time as the above optimisation studies and demonstrated that, with suitable improvements to chamber vacuum pumping speed as designed into the LAC, the 3 hour load to unload cycle required for production in the Capacity Ten-Seven plant was feasible.

Whilst this effectively achieved the result required for the Capacity Ten-Seven project, it was still considered worthwhile to investigate the two additional materials options; a-Si:C based first cell layers, and microcrystalline based second cell layers.

The a-Si:C trials were reasonably successful, depositing the required wide bandgap material in both p doped and undoped forms. However, work to replicate standard process single cell performance using these materials was unable to achieve the same performance level, with the best performance being below the 16W panel target, as shown in Figure C.7. Inclusion of these materials into the tandem structures

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[14] It should be noted that this performance comparison is made on the basis of initial panel performance – i.e. before S-W degradation effects. The limited amount of long term testing performed on these panels indicated that, as is expected, the dual junction plate is less affected by S-W degradation and therefore achieves an equivalent 'stabilised' performance.

unsurprisingly also failed to match the previous best performance and, in view of the limited time and resource available prior to LAC delivery, the a-Si:C work was terminated.

Development of a realistic micro-crystalline deposition process proved beyond the capability of the deposition system, either at the time of the trials or as planned for the LAC. Whilst it was shown to be possible to deposit the required microcrystalline material, only very low deposition rates were achievable (due to RF power limitations) and the process was therefore deemed unsuitable for inclusion in the Capacity Ten-Seven initial plant design. Trials were therefore terminated prior to any extensive optimisation work and accordingly the value of micro-crystalline Si layers in future, more developed deposition plant is as yet undefined.

Results: Solar Panel Production: LAC single junction process development

Following establishment of good uniformity conditions, single junction development has progressed rapidly, with small area devices of 1cm^2 providing the basic performance data for process tuning. A limited number of 66cm x 33cm PV panels have also been fabricated and show the materials to be compatible with standard processing techniques – albeit requiring conversion of the laser patterning holder system to eliminate the current labour intensive and unreliable manual loading and positioning that is required.

We have now achieved single junction performance equivalent to 6.4% solar conversion efficiency (pre-stabilisation). This is comparable with current production based PV panel and meets the objective of demonstrating the LAC capability to deposit a-Si based cells suitable for use in a commercially realistic product. Figure C.8 shows current best (normalised) data for a LAC deposited single junction; scaling this to full 125x66cm panel yields a performance in excess of 50Wp, significantly exceeding initial full panel targets for recommended LAC work beyond project completion (see recommendations below).

Solar Panel Production: LAC dual junction process development

There has been little time to transfer the previously derived (small chamber) TDU dual junction processes to the LAC, though the derivation of the process conditions to achieve single junction performance have allowed rapid progress in the time available. This work has confirmed that the LAC introduces no new factors into the work and should allow previously determined TDU dual junction process sensitivities to rapidly enhance performance.

Current best dual junction (normalised) performance is limited by series resistance problems (hence low fill factor), most probably resulting from non-optimum p layer thicknesses. However, we are achieving the expected doubling of Voc to 1.6V+ and Isc of about 6mA/cm^2 under 100% sun illumination, providing an excellent baseline for further optimisation.

As before, limited processing of dual junction PV panels (66x33cm) has been accomplished using standard ICP processing, though in this case the residual non-uniformities more seriously attenuate panel performance due to the inherently more sensitive dual junction. These confirm that, with optimisation, the full panel dual junction product will be readily achievable using the final TDU / LAC deposition system.

Results – Activity d) Rear Contact Deposition

Results - Rear Contact Materials Trials

None of the options trialled yielded any significant improvement in cell performance, though many showed reduced performance, largely in accordance with expectations for the materials used (e.g. lower reflectivity metals reduced generated current, materials liable to diffusion gave deterioration of electrical characteristics through the generation of ‘shunt’ resistance in the cells). Whilst initial small (1cm^2) cell trials indicated a 10% efficiency improvement using sputtered aluminium alone as the rear contact (see Figure D.2), later large area work indicated that this was unlikely to be the case and that there was no significant efficiency gain[15].

Most notably, the use of silver as a rear contact did not improve the cell current, contrary to expectation; this is believed to be due to an interaction between the silicon surface and the silver that effectively changes the reflectivity properties, requiring an additional interfacial layer (e.g. zinc oxide) to block the reaction. However, the use of interfacial layers based on suitable oxides, whilst proving compatible with the a-Si:H cells, also failed to yield enhanced performance for any of the materials systems trialled.

Subsequent work on this and other related projects has confirmed these results. Large area sputtering trials (see later section), whilst confirming the potential process, yield and throughput advantages of the sputter process, again showed no performance improvements for any of the metal and oxide combinations trialled.

Results - Coating Technology Selection

As discussed above, detailed technology review focussed on the two main PVD options – evaporative and sputter deposition.

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[15] The sputter coating process provides increased conformal coverage due to a degree of scattering of material arriving at the surface to be coated. This can and did cause a small degree of coating under the mechanical mask used to define the small area cell, resulting in an increased coating area compared to the line-of-sight evaporation process that provided the performance reference. After correcting for the differing areas, the remaining enhancement was deemed to be 'within experimental error' – i.e. insignificant.

Evaporation based PVD was the process used in current ICP production at Bridgend in the form of a 'batch' load process (i.e. many panel coated simultaneously). For the current panel size it had proven to be a highly reliable and cost effective process. However, the options review within the Project concluded that scaling up this technology was not a viable option for the following reasons:

i) Increased panel size ideally required a commensurate increase in chamber capacity, essentially quadrupling the system footprint, increasing the chamber volume (and thereby vacuum pumping requirements) by almost a factor of ten and thereby disproportionately increasing system cost.
ii) The option of maintaining current chamber size and reducing batch load was not viable due to scribe line edge coverage and therefore rear contact continuity being compromised by line of sight issues from the evaporation source. Whilst multiple sources and more complex panel rotation could be implemented to overcome this, again this raised system cost disproportionate to the increased throughput.
iii) There was an unproven concern that an inability to pre-clean the evaporation source before deposition (as in current systems) might be compromising yield and long term operation of panels. If this were so, then larger panels might be worse affected and it was therefore prudent to consider shuttering schemes – these would also raise system costs, especially for the larger, potentially multiple source systems. Material wastage would also be increased, leading to increased process costs.

It was concluded that in-line coating systems operating on a continuous basis and sequentially coating one panel at a time provided the best and most readily available solution to all these issues. Further consideration of the limitations of a continuously operating evaporative source – primarily plate feed and orientation concerns – indicated that the sputter deposition technique was the best potential fit to the Capacity Ten-Seven requirement and accordingly this technique has been the one focussed on by the Project practical work.

The sputter technique is the most widely used rear contact deposition technology in the large area thin film PV market – as well as being extensively used throughout the coatings industry in general, from precision films for photo-electronic devices to very large area architectural coatings (e.g. heat reflecting glass). It is a highly developed and proven technology, and reliable COTS systems are widely available from numerous suppliers. The Capacity Ten-Seven plant could be readily equipped with a COTS sputter system suited to the panel sizes and throughput required (or larger) at minimum risk; vertical orientation and reliable plate feed mechanisms might require a degree of customisation, but this is also low risk.

Extensive experience of sputter techniques – including design, build, commissioning and use of large area in-line commercial systems – existed within the consortium (primarily in PQL). The Project was therefore readily able to determine that this represented a very low risk route to production, requiring only that a few decisions be made as to rear contact materials options that were to be supported and any special requirements resulting from the Capacity Ten-Seven process strategy (e.g. vertical plate orientation). Work directed at determining these requirements formed the basis for the majority of the Project practical work.

Results - Rear Contact Process Trials

The sputtered aluminium rear contact films have, as expected, shown excellent adhesion, very low stress and near bulk electrical resistivity – i.e. near ideal thin films. Small area PV panels have been laser patterned with no appreciable difficulty, save adjustment of the laser parameters, and with no adverse post processing problems (e.g. no layer delamination from the laser cuts).

Examination of edge coverage also shows that the required conformal coverage is readily obtained – i.e. the 'shadowing' observed in some regions of flash evaporated samples is eliminated.

Consideration has also been given to feed through rates – critical in minimising capital and process costs. Typically, an aluminium rear contact is 100 – 300 nm thick (depending on panel manufacturer); ICP currently use 100nm. For a standard sputter system using a planar rectangular target of length comparable to the plate width, i.e. 66cm, a deposition rate of at least 100nm/min onto a 30cm wide zone is reasonable. Thus a single 122cm long plate traversed continuously under the target[16] can be coated with the required 100nm of rear contact material in less than 5 minutes. I.e. the sputter system capacity should be approximately 72 plates per 8 hour shift and two sputter deposition systems should prove adequate to meet the 192 plate per shift output from the deposition systems[17].

For the PQL technique used for this work, a much higher capacity is possible. The average deposition rate in a production system will be 400nm/min over a 45cm wide aperture, under which the plate is traversed lengthwise. Thus each 122cm long plate can be coated with 100nm of rear contact material in 1.2 minutes. In addition, the system is able to coat 2 plates simultaneously (see figure D.3), yielding a throughput capability of 800 plates per shift for a single system, well in excess of the requirement. For this reason, it is recommended that the development of this technology be monitored post project.

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[16] The aperture allows full width uniform coverage of the plate.

[17] Note that the second layer in a multilayer system is far thinner and therefore does not change this capacity.

Results – Activity e) Cell Isolation

Work on this activity progressed according to plan throughout the project. The one year project suspension proved beneficial, as Exitech continued vertical laser tool development in order to address the flat panel display market, thereby solving many of the technical issues present in the first design unit.

Initial process trials to prove the laser patterning capability of the proposed laser systems were completed early in the project and confirmed that optimised standard laser patterning would fully meet all the Capacity Ten-Seven project requirements. Process parameters were established and proven that met or exceeded all the laser patterning goals and cell isolation requirements, including the major activity objectives of narrow line front contact scribing, clean scribe edges, rear contact scribe and high voltage cell isolation[18].

ICP acquired new lasers of comparable capability (for the smaller 0.92m x 0.32m production panels) during the last year of the project and have proven these processes in full production. Accordingly, all technical risk regarding the patterning element of the Capacity Ten-Seven requirements has been eliminated.

The additional trials aimed at establishing the viability of lower cost cell isolation / interconnection schemes were also successful, proving that the laser systems specified for the initial Capacity Ten-Seven plant would be capable of meeting the more advanced, but lower cost, process with only moderate modification[19].

The first (vertical processing) laser tool design and prototype trials rig is shown schematically in Figure E.2. This tool readily met or exceeded all the Outline Requirements. The build and trials performed on the test rig proved the effectiveness of the more advanced elements required to support vertical processing, effectively de-risking the technical elements of this design.

In the second (horizontal) tool design a high rate was still achieved by the use of scanners to move the beams quickly. Foot print was kept modest by the use of split motion axes (optics on one axis and panel on another) and plate focal plane positioning was still achieved by the use of air pucks and floating optic heads. A schematic of the two laser head version of the tool is shown in Figure E.3.

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[18] It should be noted that the trials were for standard glass based solar panel, the defined ‘baseline’ Capacity Ten-Seven product. Laser patterning of other product options within the overall Capacity Ten-Seven design remit was effectively covered under other projects and therefore required no further work within this Activity.

[19] Long term stability and reliability of the alternate scheme will need to be proven before committing to the revised process. These trials were beyond the scope and duration of the project.

Cost studies have been completed for both systems. These confirm that the new design is expected to cost about 800k€, some 100k€ less than the equivalent first design tool.

It should be noted that these tools are now commercially available from Exitech, such was the success of this element of the project. The initial commercial Technical Specification of the second (horizontal) laser tool is included as an Appendix to this report.

5. DISCUSSION

Although constrained by more limited time, equipment and facilities availability than originally anticipated, the Project work has been concluded successfully to meet the Project goal of defining the critical elements of the Capacity Ten-Seven production plant design.

Broadly, the outcome of the work showed that the project precept was correct. I.e. concentrating on optimising cell structure and plant design to achieve best overall production efficiency, as opposed to best PV conversion efficiency, could provide the basis for a highly cost competitive solar PV product.

However, at the detail level, some of the results did not conform to our initial expectations. These are discussed in detail below.

Discussion – Activities a) Fundamental Studies and f) Initial Design Study

The work under this activity largely confirmed initial expectations regarding the likely optimum cell structures and the plant that would be required to produce these – at least within the project constraints. Two elements gave the expected optimum solution, though for substantially different reasons to those that had been expected.

The first was that the dual junction structure proved far more cost effective than the standard single junction purely on the basis of production cost – in fact, a small drop n performance was tolerable when considering the achievement of the '$/W' targets. This had major (beneficial) repercussions within the later Semiconductor Deposition Activity (reported later).

The second was that some initial concerns regarding mixing in-line and batch processing units proved unfounded, with the combination plant proving to be the optimum design, especially from a reliability and versatility point of view. Essentially, the need to 'buffer' stocks of plate at either end of the batch processes provided a means of improving plant reliability though the provision of 'hold' points to cope with throughput disruption. These were ultimately repeated in the design at the in-line systems and would also have had to be implemented in a fully in-line plant to achieve comparable reliability, essentially eroding any cost and throughput benefit from the latter. The added versatility of the more modular 'batch' based plant also more readily supported alternate later product or technology upgrade.

As expected, the analysis also showed the semiconductor deposition and cell isolation laser patterning systems to be the items most requiring development within the project. Front and rear contact technologies were also addressed separately as planned, although these did not yield the expected outcomes (as reported below).

Within this Activity, the final work addressed the infrastructure required for the Capacity Ten-Seven plant. This has now been fully assessed and, where necessary, defined or specified. Specifications have been obtained for Commercial Off The Shelf (COTS) solutions for further key systems that were identified as needing confirmation of performance and these have all been assessed as meeting the Capacity Ten-Seven plant requirements. These are automated wash facility, inter process plate handling and transport, buffer storage and automated solar I-V tester. Options that have been identified for other systems and design changes have been put on hold, as the optimum solution will depend largely on legislation and COTS systems available at the time of final plant design. These are the hazardous gas abatement strategy (2 COTS techniques, multiple COTS equipment available) and the gas panel re-engineering (current designs meet safety legislation, despite appearing unsafe to us; re-engineering would need new safety approvals).

The remaining decisions regard the final process flow and systems integration to be adopted, and are strongly dependent upon the final product(s) that the plant will provide. This is currently undecided and we have therefore kept the options as open actions for further consideration beyond the project.

Discussion – Activity b) Front Contact Deposition

The first front contact assessment report concluded that there was little to choose between bought in tin oxide coated glass and in-house production; cost and security of supply favoured in-house production, but this was offset by reliability concerns and unresolved cosmetic issues with the available APCVD equipments[20]. Accordingly, it was recommended that the Capacity Ten Seven plant buy in commercially available product, at least initially.

The later addition of zinc oxide as a future preferred front contact actually strengthens the argument in favour of the ‘buy in’ option. The zinc oxide process itself, though potentially yielding a 10% - 15% improvement in cell performance for no significant additional cost, is judged to be an insufficiently mature technology at present. The level of risk in changing to this material, though only moderate, magnifies

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[20] On cost, coating in-house would be cheaper only if operating at full capacity. However, as soon as a situation arises where the plant falls below capacity the cost benefits reverse and the return on investment begins to look poor. If we also take into account the fact that we are unsure of the yield on the in-house processed glass in large areas, and given that the manufacturer would not be willing to put a guarantee on this, we conclude that the risk in purchasing a £1.5m in-house APCVD plant is high and not recommended.

potential problems with a-Si deposition process optimisation and thereby raises overall production risk to a high level.

However, it is highly probable that this situation will change in the next few years as there is substantial academic and commercial R&D in progress to develop the material and commercial processes. Purchase of an APCVD system for tin oxide deposition at this time would consume capital that might be better spent later on a zinc oxide deposition system. Until the zinc oxide technology is more mature – and the cost-benefit balance much clearer – it would therefore be unwise to commit the plant to a particular technology.

The buy in of commercial product has the sole risk of security of supply. However, in mitigation there are multiple sources of supply and the risk is judged to be low. To keep this in context, the tin oxide coated glass feedstock needed for a 10MW solar module plant can be produced by one vendor in a few days of production. Additionally suppliers have been demonstrably willing to develop their material to meet specific customer requirements (for large purchases) and it should therefore be possible to obtain optimised product for the Capacity Ten-Seven plant without incurring in-house development costs. From a performance and risk viewpoint, the 'buy in' option therefore remains the recommended choice.

However, it is also clear that the current developments in front contact technologies need to be closely watched, as the situation could change rapidly. In particular, contact should be made with Unaxis-Balzers to establish whether materials could be acquired for in-house trials as direct experience of using the material is likely to provide a more informed, changed assessment of the technological risk.

Discussion – Activity c) Semiconductor Deposition

Overall, this work progressed near to plan, despite unexpected delays and process complexities, delivering the required information and results to demonstrate the viability of the planned Capacity Ten-Seven plant Semiconductor Deposition plant and process – a dual junction a-Si based cell deposited using a batch load, low cost PECVD system.

The initial cell and materials selection trials provided some unexpected results. We were never able to achieve the expected 10% better initial solar conversion performance from the dual junction cells (compared to single junction equivalents), despite trying a wide range of options reported in the literature. Our final assessment of this was that – as in the case of the Back Contact work – this gain could only be realised by an integrated programme of overall cell optimisation, i.e. one that added in contact materials variation to the cell optimisation. Within the resource and time limits of the project, this was not feasible.

However, achieving improved performance was not a major target of the dual junction development, as this was not the basis of the cost savings that underpinned its selection as the preferred option. The Capacity Ten-Seven fabrication process required only that performance be equivalent to single junction performance – it was far more critical that the deposition time be no more than 3 hours and that no unusual or expensive materials or processes be required in its fabrication. As reported, this was achieved, allowing concentration on the second aspect of the work, proving the low cost deposition design.

Once the LAC was in use, the achievement of basic uniform deposition conditions was a more complex problem than originally envisaged. This was due to the expected complex interdependence of the contributing process conditions, compounded by previously underestimated gas flow impact on indicated process pressure. (The latter represents significant new process 'know-how' and is a valuable outcome of the LAC work in its own right.)

With the process induced uniformity issues resolved, the LAC finally showed a number of remaining sources of minor non-uniformity; as these will detrimentally affect full size panel, they need resolving within a production design. The design requirements have been determined and could ideally be trialled within the existing LAC prior to committing to a new production chamber design.

Assuming that these design changes are implemented, the smaller area PV characterisation has shown that there are no intrinsic difficulties with depositing good quality a-Si based solar PV junction devices – single and dual junction – within the LAC/TDU unit. Analysis of the current best process single cell I-V behaviour shows that there is still potential for improvement. Series resistance is higher than ideal, leading to a mediocre fill factor (0.57 c.f. 0.65 target). Good performance is still achieved as a result of a very good Isc in excess of 13mA/cm^2 and good Voc of 0.82V per cell. Based on analysis of prior process improvements, the indications are that the p (and b) layers are still thicker than optimum. Thus further process development should readily be able to achieve excellent single cell panel performance from the LAC.

Overall therefore, the design simplifications (and commensurate capital cost reductions) built into the LAC have proven viable and the LAC has achieved its project objectives of defining a low cost option for the deposition of the a-Si semiconductor layers for the Capacity Ten-Seven plant design.

One final aspect needs further consideration: the 1 year delay in the project, coupled with a current poor market for vacuum and PV deposition system sales – especially well established 'mature' systems that have already recouped their development costs - has reduced the cost of suitable Commercial Off-the-Shelf (COTS) units substantially. As such, the cost savings implicit in the LAC may no longer represent the best cost-risk balance for the future plant. This aspect needs revisiting before committing to substantial work on the new design or build of the LAC production system.

Discussion – Activity d) Rear Contact Deposition

Although constrained by more limited equipment and facilities availability than originally anticipated, the Project rear contact work has been concluded sufficiently to meet the Project goal of defining this element of the Capacity Ten-Seven production plant design. The review of scale up options for the current ICP process, backed up by trials work, shows the flash evaporation route to be unrealistic for the panel sizes and throughput required.

The sputter deposition route remains the best – and lowest risk – candidate rear contact deposition route. Our trials have shown that there are no inherent problems with either the materials or systems required for this, all technical and commercial requirements being fully met by current COTS in-line systems.

At this time, there appears to be little benefit to changing the rear contact from the current single aluminium layer to more demanding multi-layer options. For the current ICP cell structures, we have been unable to demonstrate any significant performance improvement to offset the additional cost.

This is clearly contrary to reported R&D by a large number of high class academic and industrial laboratories. We assess the reason for this as being a need to optimise the remaining cell layers – the front contact and a-Si:H junction structure – individually for each material combination; i.e. the advantage of the rear contact schemes can only be realised if the PV device as a whole is fully optimised <u>for that rear contact</u>. It is likely that the baseline ICP junction process has, over the years, been optimised such as to be relatively insensitive to rear contact variability, therefore making it an unsuitable test vehicle for the trials.

A full PV device optimisation programme falls outside the scope of the project – there are a significant number of interacting materials and processing variations that would need an estimated 12 month programme of work to achieve this. Given the apparently marginal cost-benefit that is likely to accrue (based on literature studies), this work is not considered a priority at this time. Accordingly, the final stages of the rear contact work activity focussed on clarifying any production and process advantages or issues that might arise from the use of the sputter deposition technology.

However, given that other researchers and manufacturers are able to realise benefits from such technologies, it would be prudent to ensure that the Capacity Ten-Seven plant sputter systems have capability to retrofit or be upgraded to two target systems. Most current COTS in-line sputter deposition systems will support upgrade to multiple target systems for multi-layer rear contact schemes as and when these are developed in the plant.

However, the pace of development of rear contact technology remains high, with a significant R&D effort being expended on finding means for extracting more performance from existing cell materials and structures. As such, it will also be prudent to maintain a watch on the most promising candidates in the field, particularly the zinc oxide / diffuse reflector scheme described in this report.

In summary, the sputter deposition technique meets all the requirements for the Capacity Ten-Seven plant design and is accordingly confirmed as a low risk option. Proven COTS systems exist for the full range of materials used by PV manufacturers, allowing later integration of proven multilayer schemes when these are developed.

Discussion – Activity e) Cell Isolation

The Cell Isolation work clearly demonstrated the great advances in laser patterning that have taken place in the last decade. The patterning and isolation targets set in the initial project Outline Requirements for the laser tool, though a major improvement on the Intersolar factory systems capabilities at that time, proved comparatively easy to meet – or greatly exceed in some cases – with new laser technologies.

Thus the activity largely focussed on achieving cost effective designs to achieve high throughput and reliability, allowing two substantially different options to be assessed in detail.

The first design fully met the project Outline Requirements and trials of the mechanisms need to allow the required vertical processing were totally successful. This allowed the planned Design Iteration stage to be used to look at other options for cost reduction.
The second design aimed to reduce equipment cost without compromising any areas of performance, through processing the solar plate held horizontally. This was also achieved.

However, there are 2 further issues that need to be taken into consideration when comparing the designs. Firstly, the remainder of the Capacity Ten-Seven plant is currently planned to process and transfer glass held vertically, requiring the addition of ‘re-orientation’ stages to the second tool, an additional cost estimated at 40k€. Secondly, 2 of the laser patterning steps will require the deposited films to be in contact with the transfer rollers of the horizontal tool design; this may induce abrasion damage, particularly to the a-Si film, and thereby efficiency or panel yield loss.

Thus the second, lower cost design introduces some minor technical risk to the plant design. This requires mitigation through experimental studies.

Subject to these concerns being favourably resolved, incorporation of the two designs into the Capacity Ten-Seven PCR matrix shows the second (horizontal bed) design option to be (marginally) the optimum choice for the Capacity Ten-Seven plant. Should these concerns remain at the time of building the plant, the first (vertical) design provides a marginally more expensive, but lower risk alternative.

The projected sales price for a base line IR laser based tools of the horizontal design and able to perform scribe 1 and edge deletion (scribe 4) has been calculated at 800k€. A similar tool with a single green laser only, able to do scribes 2 and 3, will be approximately 700k€. The typical time for such tools to process a single panel (for a single scribe process) is about 1 minute so that if 4 tools are operated on a single line the total capital outlay is 3M€ and the line can produce up to 1400 panels per day (or close to 15MWp per year). It has been estimated that this leads to a laser patterning cost of 1.40€ per panel, well inside the cost targets for this part of the processing. The equivalent cost for the vertical processing design is slightly higher at 1.45€ per panel, again within the cost target for cell isolation processing.

6. LESSONS LEARNED

The primary lesson learned from this project is the need for contingency planning to deal with major commercial changes, in this case the impact of losing the Prime Contractor through a totally unexpected forced liquidation.

Even with hindsight it is difficult to understand why the creditor responsible for this chose to force Intersolar into liquidation; it was clear to all other creditors – including two of the collaborators – that the Intersolar proposals for meeting its short term cash-flow problems promised substantially more return than the eventual liquidation. However, this should be taken as an indication of the unpredictability of commercial change that can occur in a 3 year project and needs consideration.

The major problem was that contingency plans were in place only to deal with the loss of a collaborator, not the Prime Contractor. A ‘succession’ policy could have been prepared and, with DTI approval, rapidly implemented with a consequent reduced delay to the project. This would have probably required a reduction in the project scope (to match the reduced resources), but could nevertheless have allowed project continuation whilst a new collaborator or partner was found. In the event, this would have been ICP, and the project team would probably have had the full 3 years of the project to complete the work – this would have allowed us to dramatically improve on the project achievements, as it was only in the last 2 months of the project that realistically uniform a-Si panel was produced to allow full panel trials and optimisation studies to begin.

A less critical lesson concerns the need to carefully segregate the project from immediate and unplanned commercial pressures, if only at the managerial level. The early successes with trial dual junction panel based on the standard ICP process led, not unsurprisingly, to a desire at all levels to see if this could be developed to a level suitable for production implementation in the existing plant at Bridgend. As such, the resources allocated to the project, staff and facilities, began to experience conflicting requirements when the project work was ready to progress to the investigation of other options and, with hindsight, this delayed some investigations. In the event this proved unimportant, as the activities proved unsuccessful in terms of providing a better ‘$/W’ option and were discounted from further development. However it would be unwise to assume this will be the case in future, and future project management needs to ensure that the project team remains focussed on project objectives and does not allow current commercial interests to distract them.

7. CONCLUSIONS

The project has delivered all the required results to meet the overall project objective of defining the parameters for the design of a solar cell process plant with a capacity about 10MWp per annum.

Cost studies show that for the preferred cell option and a number of equipment options, the production cost target of 1 $/Wp can be achieved for the standard large area (nominal 130cm by 66cm) glass based solar panels. This is less than half the cost of production of the current ICP plant.

As expected, the panel efficiency produced by the plant will not be comparable to that produced by the best rival technologies, but the cost advantage more than offsets this and is expected to result in the Capacity Ten-Seven products proving highly competitive for large area, low cost applications.

The plant design uses either well established technologies and processes or, in the case of the semiconductor deposition and laser patterning systems, uses new designs that have been developed and satisfactorily proven in this project. The plant therefore represents a low risk commercial proposition.

Outline and, where applicable, more detailed specifications and requirements have been produced for each element of the production plant, and a number of options and process schemes have been retained (and shown to be viable) to allow for anticipated short term improvements to commercially available equipment and technologies. Final decisions as to the best option will be made at the time of equipment purchase.

The Outline Plant Definition essentially considers the plant and processes in six categories: these are Overall Plant Requirements (including cell design and technology issues), Front Contact Requirements, Semiconductor Deposition Requirements, Rear Contact Requirements, Cell Isolation Requirements and Plant Infrastructure.

The Capacity Ten-Seven project trials and supporting cost modelling and performance analysis have shown that a simple dual junction a-Si based cell, largely using processes and technology current in ICP, can provide the basis for cost efficient solar panel manufacture as defined for the Capacity Ten-Seven Plant.

Other product options have been shown to be realistic within the overall plant design, though these in the main require further development under other projects. These provide the potential for the Capacity Ten-Seven plant to address the potentially large Building Integrated PV market with low cost products that also permit low cost installation schemes to be realised, an essential requirement if this market is to realise it’s potential.

For the Front Contact technology, the balance of cost, performance and risk indicates that it is best to buy in commercial product for the Capacity Ten-Seven plant initially. In house tin oxide coating, or the use of zinc oxide based products are also options to be considered in the longer term.

The suppliers for tin oxide coated glass have a highly developed, reliable process and are willing to develop their material to meet specific customer requirements (for large purchases). It should therefore be possible to obtain optimised product for the Capacity Ten-Seven plant without resorting to in-house development.

Purchase of in-house equipment for tin oxide front contact deposition, although preferable from a long term cost point of view, has a higher technical risk and, should the rival (and incompatible) zinc oxide process technology develop to a mature commercial process, runs the risk of becoming redundant before capital pay back time is achieved.

The zinc oxide based product, though potentially yielding a 10%+ improvement in cell performance, is judged to be an insufficiently mature technology at present. The level of risk in changing to this material, though only moderate, magnifies potential problems with a-Si deposition process optimisation in particular and thereby raises overall production risk to a high level.

The Capacity Ten-Seven project Semiconductor Deposition trials have vindicated many elements of the new Large Area Chamber (LAC) design and in the process provided much new knowledge, experience and expertise in handling and developing large area PECVD.

Overall, the LAC has been demonstrated to provide a sound basis for a low cost semiconductor deposition chamber for the Capacity Ten-Seven plant design. Further opportunities for cost reduction and improved operational capability have arisen from the practical work.

a-Si based single and dual junction PV panels of 1250x660mm area have been successfully deposited in the system, confirming the overall suitability of the LAC/TDU system as a basis for a future production tool. Panel performance has been assessed on sub-elements of these (due to current processing limitations) and has confirmed adequate PV performance, within the limits of residual system non-uniformities.

The TDU/LAC design is currently of a standard that requires only minor redesign and some further proving trials to form the basis of a prototype production tool. Design changes have been identified for future development and trials prior to committing to a final production system design.

The project work on rear contact selection and techniques shows that in-line sputter deposition using COTS equipment should be the technique of choice for the Capacity Ten Seven plant design.

The sputter deposition technique meets all the requirements for the Capacity Ten-Seven plant design and is accordingly confirmed as a low risk option. Proven COTS systems exist for the full range of materials used by PV manufacturers, allowing later integration of proven multilayer schemes when these are developed.

At this time, a simple aluminium rear contact will provide an adequate initial product for the plant, though once baseline production is reliably underway, use of a more complex multilayer rear contact – most likely the widely used zinc oxide / aluminium combination – may allow some improvement in the cell response as part of a longer term optimisation exercise. Accordingly, it is important that the equipment have the flexibility to incorporate this extra step at a later date.

The Capacity Ten Seven plant rear contact deposition system should therefore be a COTS in-line sputter deposition system, with a throughput in excess of 100 plates per 8 hour shift. The material to be deposited is 100nm of aluminium. The system should have the capability to be upgraded to a two target system for multi-layer rear contact deposition at a later date, most probably a zinc oxide / aluminium structure.

The Cell Isolation Activity has demonstrated the suitability of laser patterning to meet all the Capacity Ten-Seven requirements for monolithic integration of the required thin films. The work has delivered two effective designs for modular PV panel manufacturing tools. The preferred design has a low cost of ownership of about 1.4€ for a 0.66 x 1.3m panel.

The preferred design includes a higher level of technical risk than the alternate option. This will be addressed in post project trials prior to deciding between the two. It should b noted that either design is suitable for use in the Capacity Ten-Seven plant and that this element of the equipment specification is now considered to be able to be addressed through 'low risk customised COTS' systems – i.e. existing commercial equipment with minor modifications to address the specifics of the plant design.

The full infrastructure required to support the key deposition and patterning systems for the Capacity Ten-Seven outline plant design has been defined. Whilst decisions are still required regarding process flow methodology and detail, all the systems and equipment required to support any of the options are readily available as COTS items or capability. The infrastructure therefore represents a low technical and commercial risk to the Capacity Ten-Seven plant design.

8. RECOMMENDATIONS

The major recommendations from the project are obviously subsumed within the Outline Plant Definition and supporting documents that will form the basis of the Capacity Ten-Seven detailed plant design. These recommendations fall outside of the scope of this report due to IPR and other commercial constraints.

However, within each of the Activities, there are a number of lesser recommendations that will address choice of options, or provide mitigation of residual technical risks. These are dealt with in this section.

1. For the Front Contact Technology, it is recommended that a close watch be kept on the development of the zinc oxide technology and, if the opportunity arises, material should be acquired for trials. A successful zinc oxide technology – including washing and patterning processes – could be readily implemented into the plant design and has the potential to greatly improve cell efficiency and the '\$/W' cost of production accordingly.

2. For the Semiconductor Deposition Task, it is recommended that a LAC/TDU design review be conducted to document, detail (and justify) the revised design and process requirements. Some additional risk reduction work could still be conducted using the TDU in its current state and it is further recommended that this be considered prior to committing to building a new LAC to the revised design. The recommended development strategy is:
i. Relocate the TDU/LAC to ICP Bridgend to increase trials throughput.
ii. Implement only minor essential changes required to support further trials or answer critical questions.
iii. Prove reasonable performance full size PV plate capability – i.e. eliminate the residual non-uniformities. (Target – 35Wp initial performance)
iv. Complete system furnishing in line with this report.
v. Develop processes for good quality, high performance full size PV plate – nominal 40Wp stabilised.

For the Rear Contact Activity a technology watch should be maintained generally on emerging rear contact related technologies, specifically the Chemical Vapour Deposition (CVD) technology for zinc oxide overlain with a white 'backscatter' material recently reported in the open literature. A further development that should be monitored is the large area advanced sputter deposition technology under development by PQL, which promises to provide very high capacity rear contact metallisation at substantially lower cost than current in-line sputter systems.

For the Cell Isolation Activity, the remaining uncertainty regarding the choice of system designs can best be resolved through comparative process yield trials on the two systems. It is anticipated that both systems will be available as commercial units in the near future, the vertical system primarily to address the needs of the large area flat panel display industry, the horizontal system to address the more cost constrained PV market.

Finally, the project has met its target to define and prove the viability of a solar PV production plant with a capacity of 10MWp p.a. and a cost of production of less than 1$/W. This fully accords with the initial Intersolar aims when first proposing the project. Therefore we recommend that more detailed design studies – aimed at fully specifying and identifying the systems and infrastructure to be purchased – be started as soon as possible in order to rapidly capitalize on the commercial lead that this project has provided for ICP and its collaborators.

9. ACKNOWLEDGEMENTS

ICP and their collaborators would like to acknowledge the essential financial support provided to this project by the DTI.

We would also like to acknowledge the help and support of the various Project Officers and staff of FES (originally ETSU) who assisted throughout the project, particularly in the definition of the contract and project changes that ultimately enabled continuation following the loss of the original Prime Contractor.

FIGURES

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Figure A.2: Schematic of Customised COTS Large Area Plate Handling Systems

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Figure C.2: Photograph of a Plate Set from Initial LAC Deposition Run (high RF power)

Figure C.3: Photograph of a Plate Set from Initial LAC Deposition Run (lower RF power)

Figure C.4: Plate Set from Revised Configuration LAC Deposition Run – higher RF power

Figure C.5: Full Size Plate from Final Configuration LAC Uniformity Trials

Figure C.6: Measured Solar Performance Characteristics for Dual Junction Cell based Solar Panel deposited using ICP 'Standard' Layer Processes

Figure C.7: Measured Solar Performance Characteristics for a-Si:C based Solar Panel

Figure C.8: Normalised I-V and P-V data for LAC deposited single junction a-Si solar cell. Scaled to 100% sun equivalent (from 61% actual).

Figure D.1: Rear Contact metal discontinuities at TCO scribe resulting from 'shadowing' of deposition ('flash' evaporation system)

Figure D.2: Comparison of Sputtered and Evaporated Aluminium Rear Contact on Cell Performance: Tandem Cell (SiC Process) – 1cm^2 cells.

Figure D.3: Schematics of PQL 'Linear Target' Sputter Deposition System

Figure E.1: Outline Monolithic Integration Schematic for a-Si based Solar PV Panel

Figure E.2: First Design (Vertical Processing) Laser Tool Schematic

Figure E.3: Second Design (Horizontal Bed) Laser Tool Schematic

FIGURE A.1

Outline Project Ten-Seven Plant Design Schematic

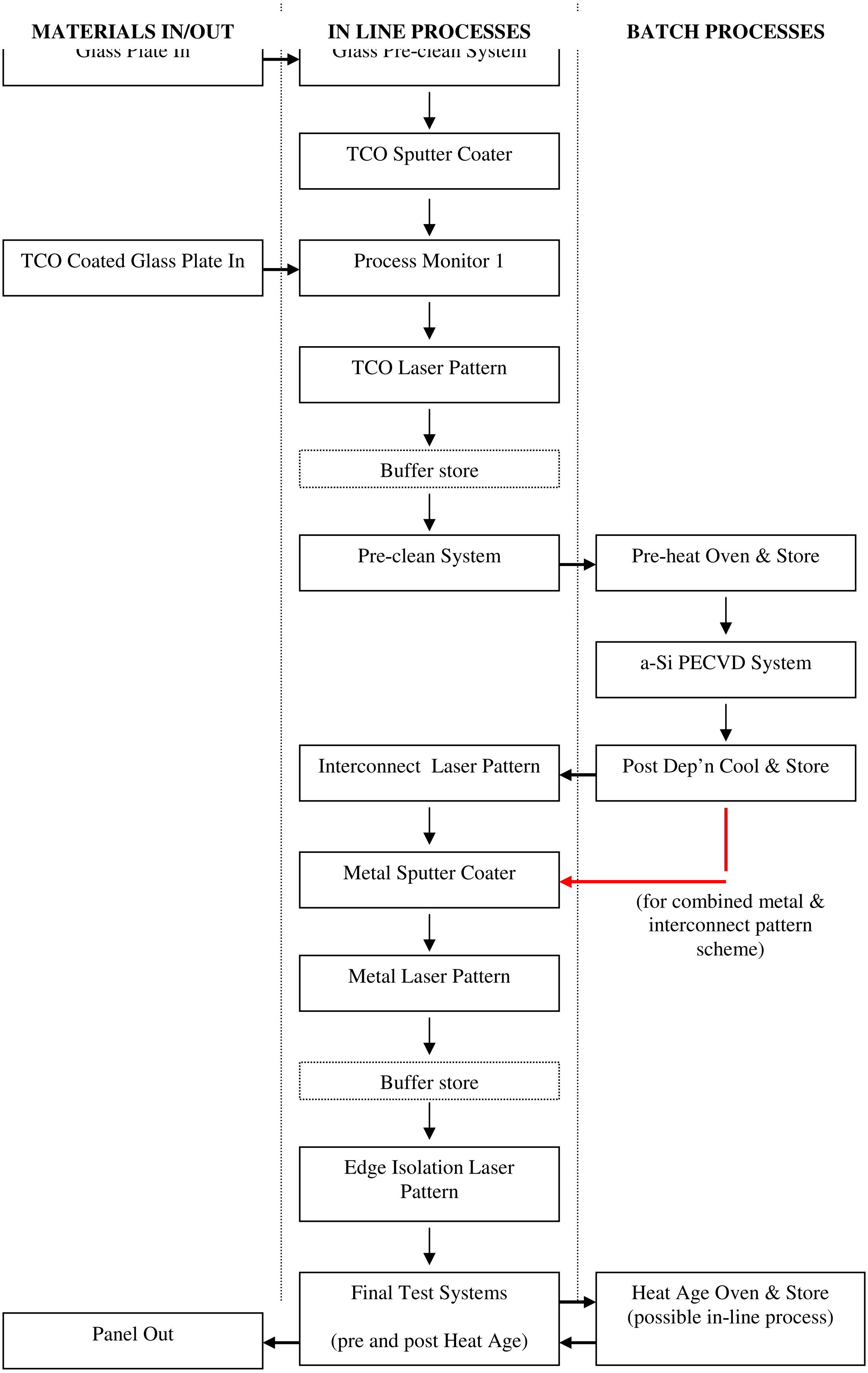
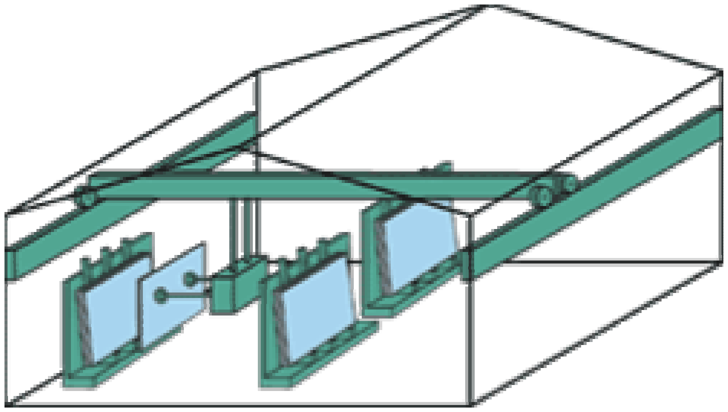


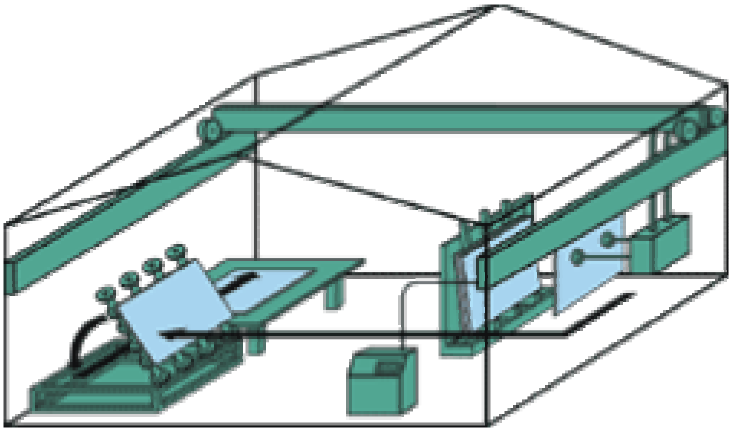
Figure A.2

Schematic of Customised COTS Large Area Plate Handling Systems

(a) Vertical to Vertical Transfer



(b) Vertical to Horizontal Transfer



Note: Systems shown operating within environmentally controlled space; this eliminates the need for full factory clean conditions

Figure C.1
General View of the LAC and original chamber TDU prior to integration at PQL in November 2004

TDU chamber
8 off 92cm x 33cm plates

LAC
48 off 125cm x 66cm plates

Figure C.2

Photograph of a Plate Set from Initial LAC Deposition Run (high RF power)

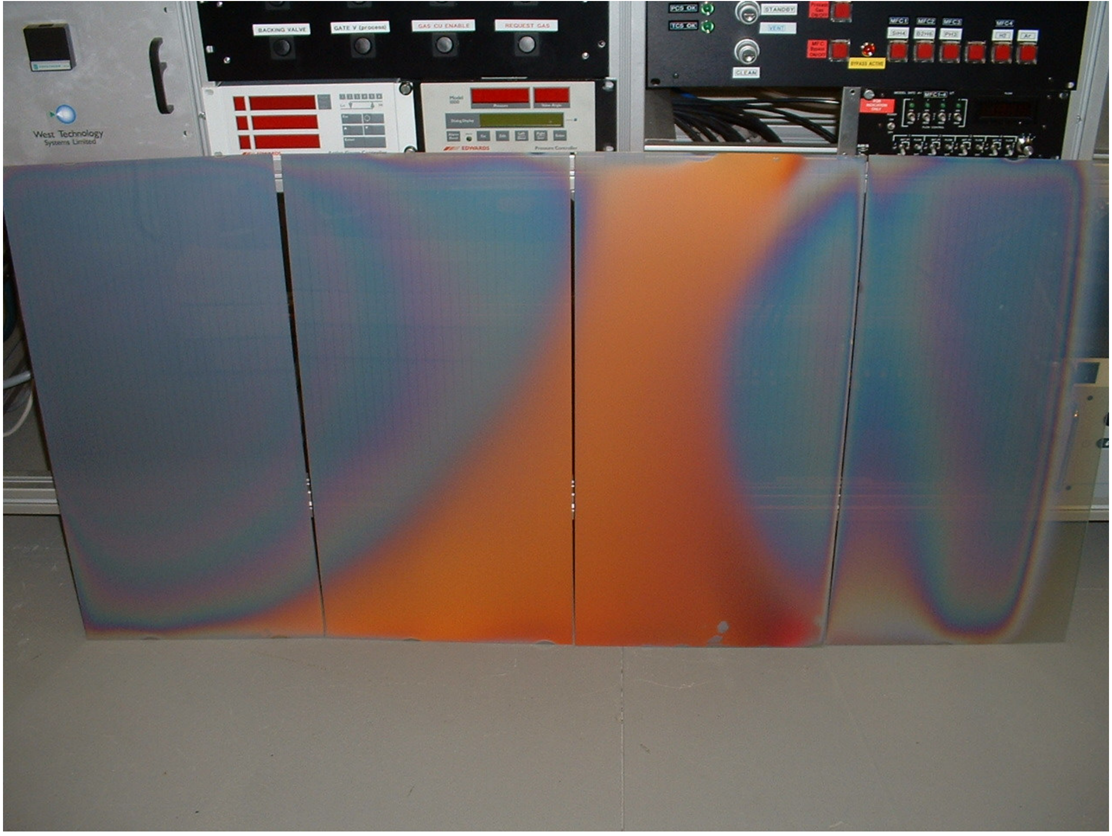


Figure C.3

Photograph of a Plate Set from Initial LAC Deposition Run (lower RF power)

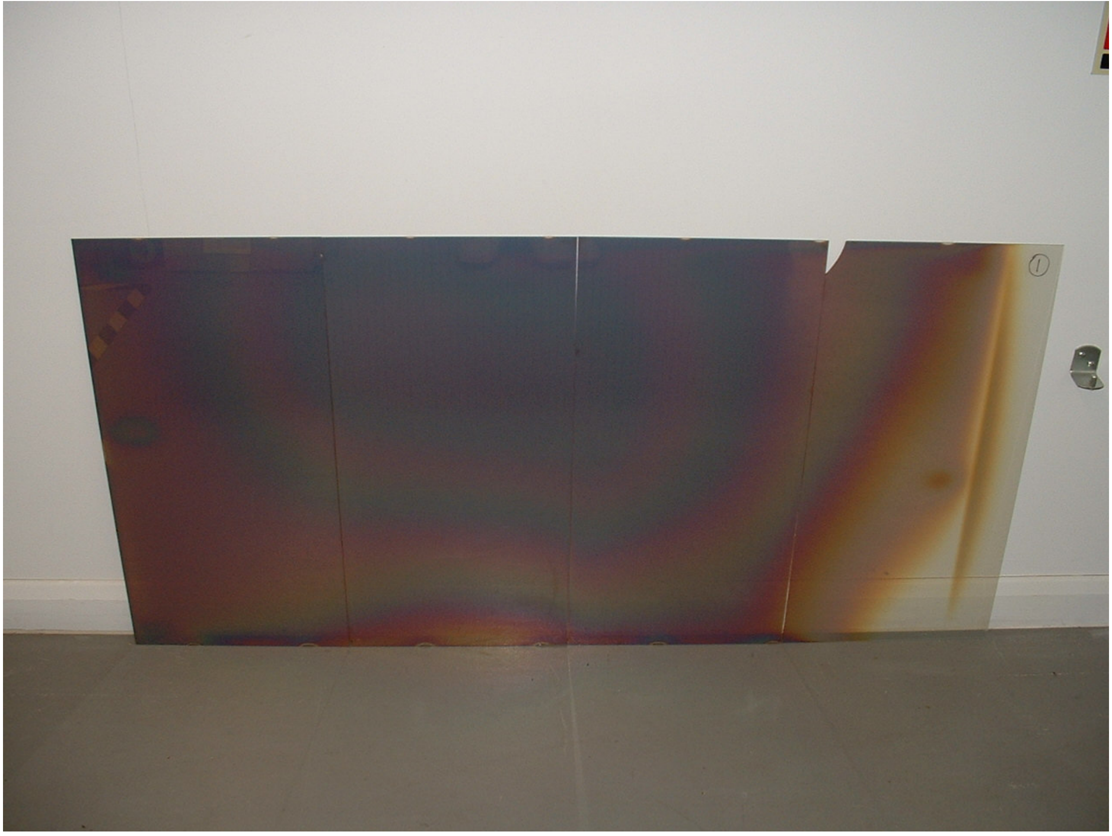


Figure C.4

Plate Set from Revised Configuration LAC Deposition Run – higher RF power

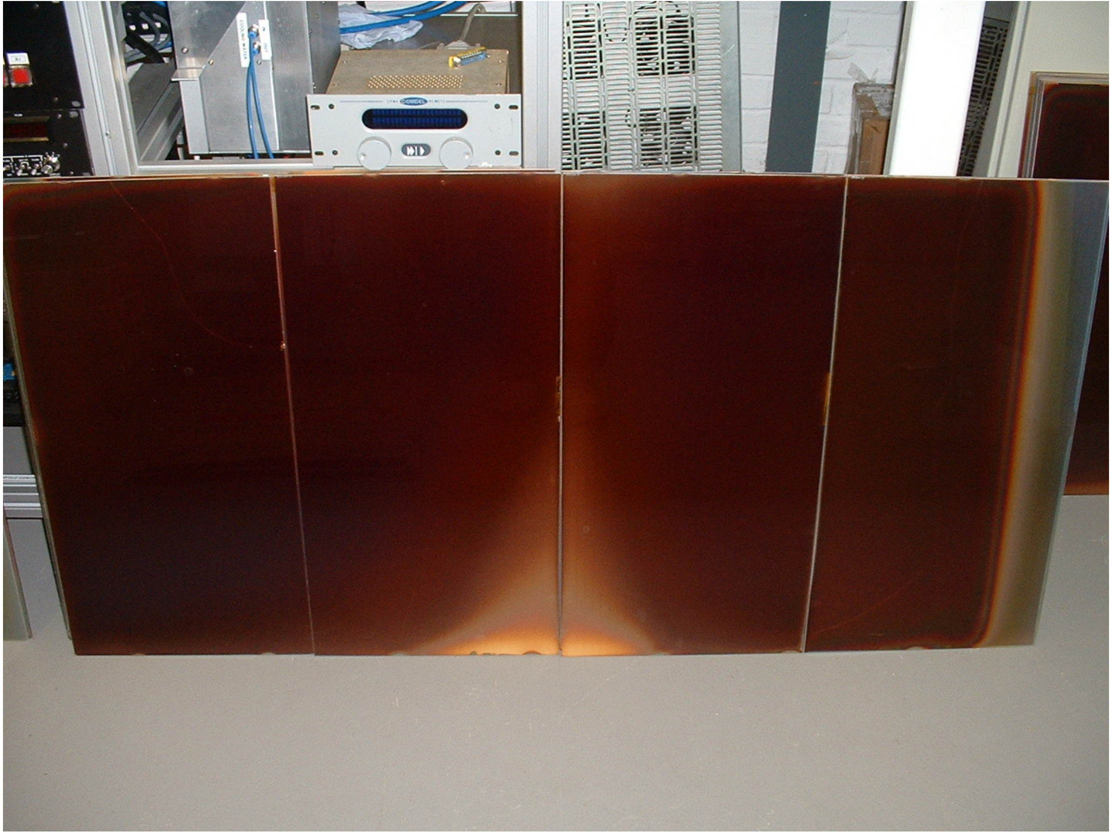


Figure C.5

Full Size Plate from Final Configuration LAC Uniformity Trials

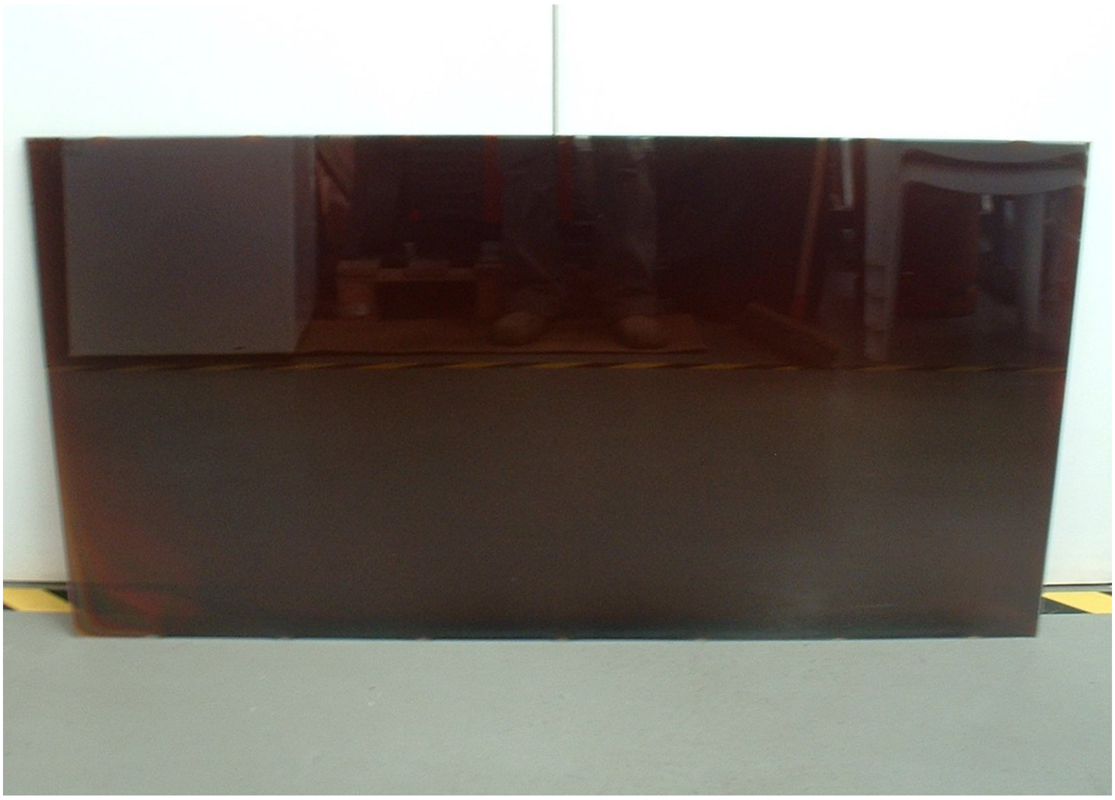


Figure C.6

Measured Solar Performance Characteristics for Dual Junction Cell based Solar Panel deposited using ICP 'Standard' Layer Processes

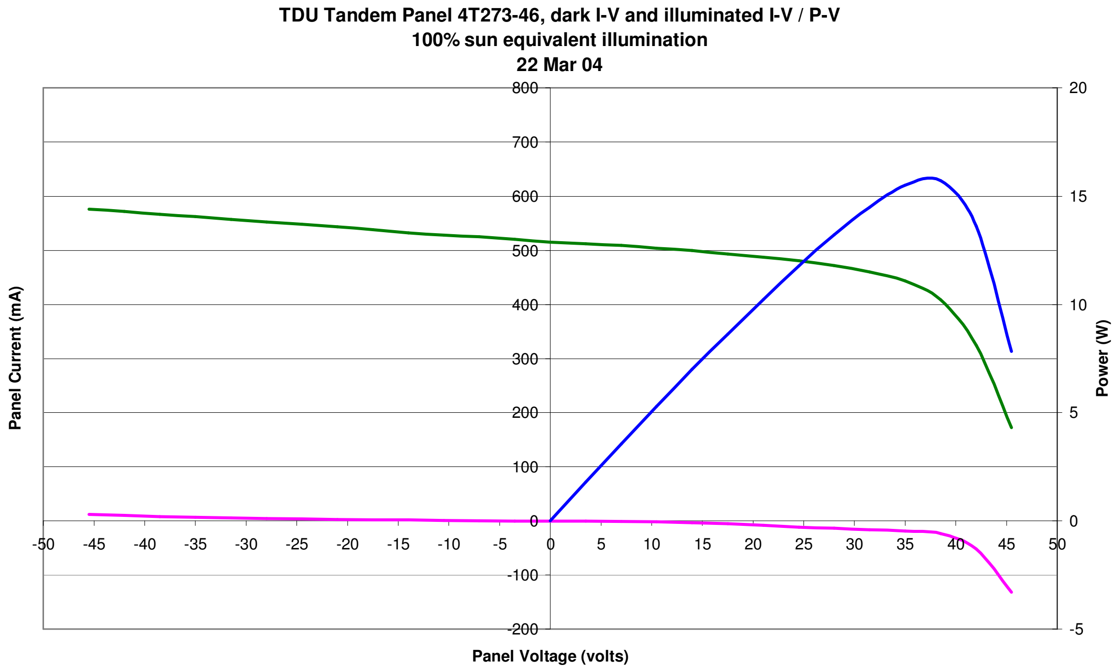


Figure C.7

Measured Solar Performance Characteristics for a-Si:C based Solar Panel

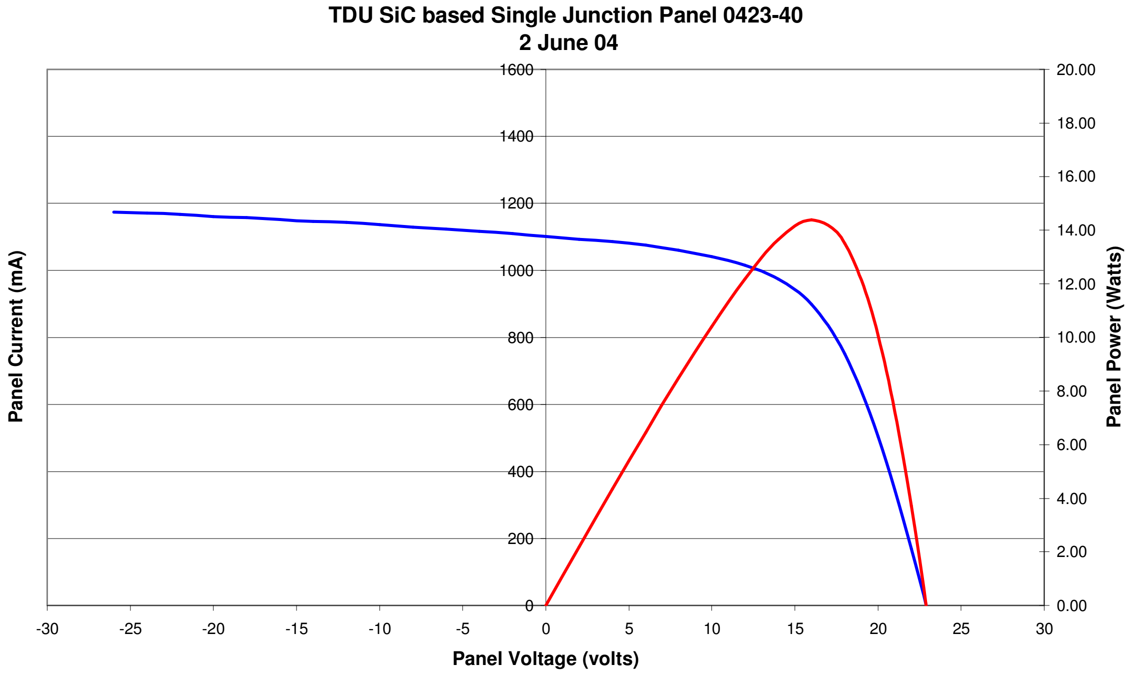


Figure C.8

Normalised I-V and P-V data for LAC deposited single junction a-Si solar cell. Scaled to 100% sun equivalent (from 61% actual).

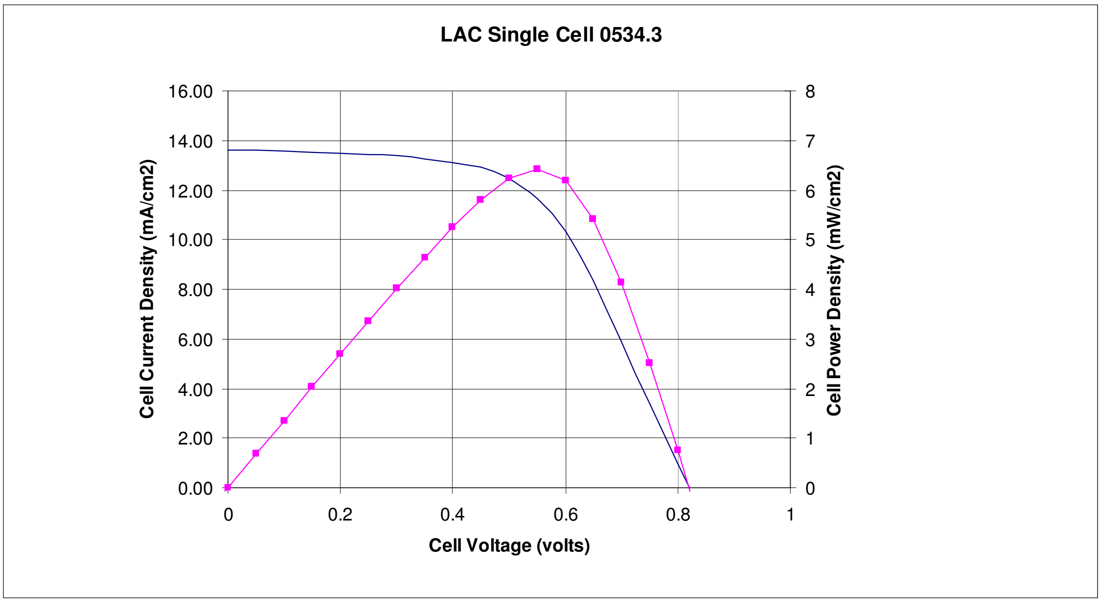


Figure D.1

Rear Contact metal discontinuities at TCO scribe resulting from 'shadowing' of deposition ('flash' evaporation system)

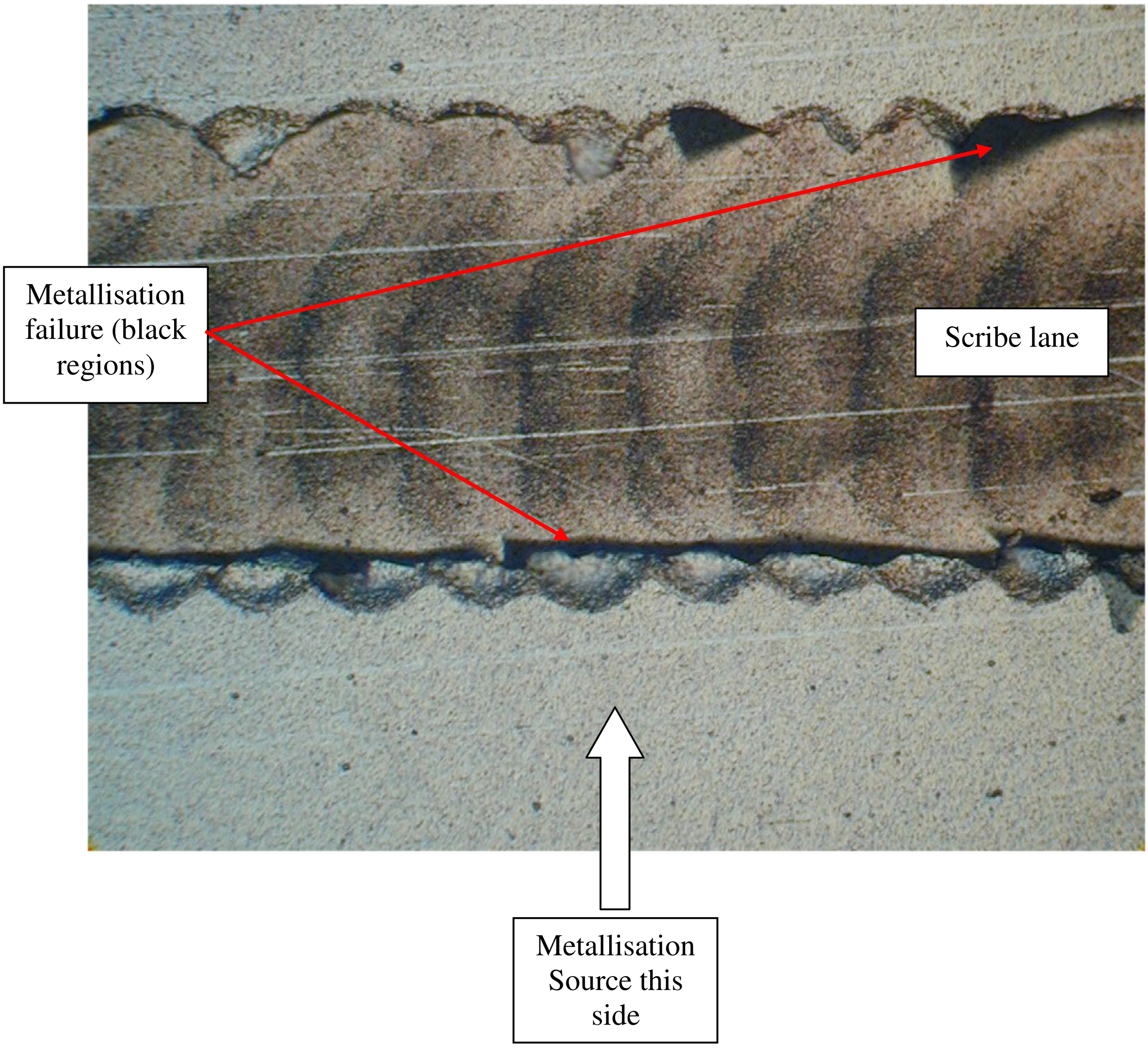


Figure D.2

Comparison of Sputtered and Evaporated Aluminium Rear Contact on Cell Performance: Tandem Cell (SiC Process) – 1cm^2 cells

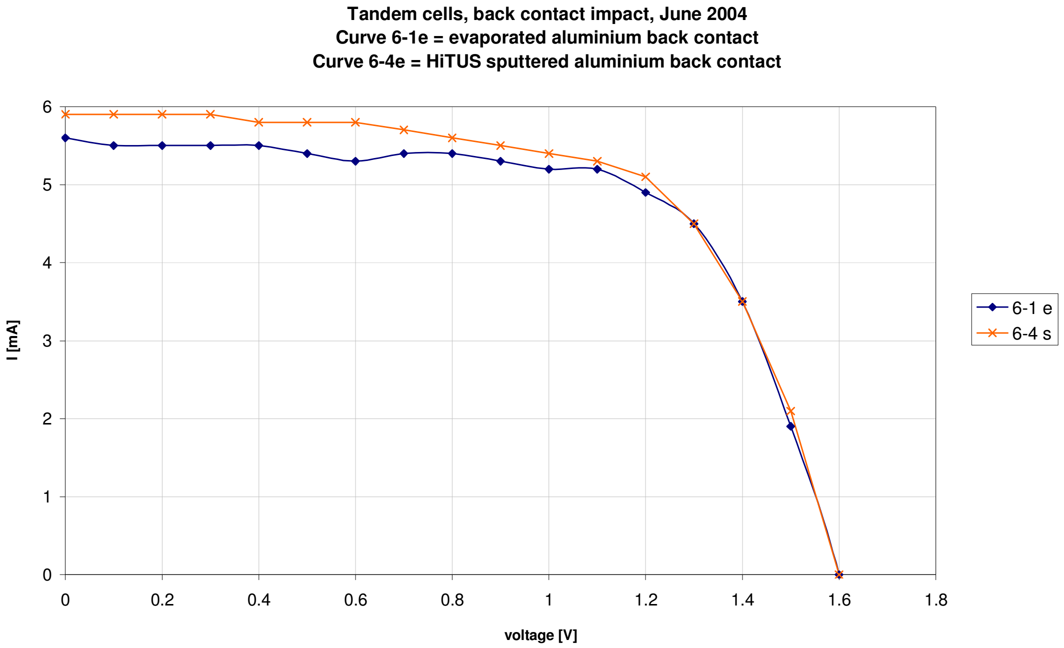
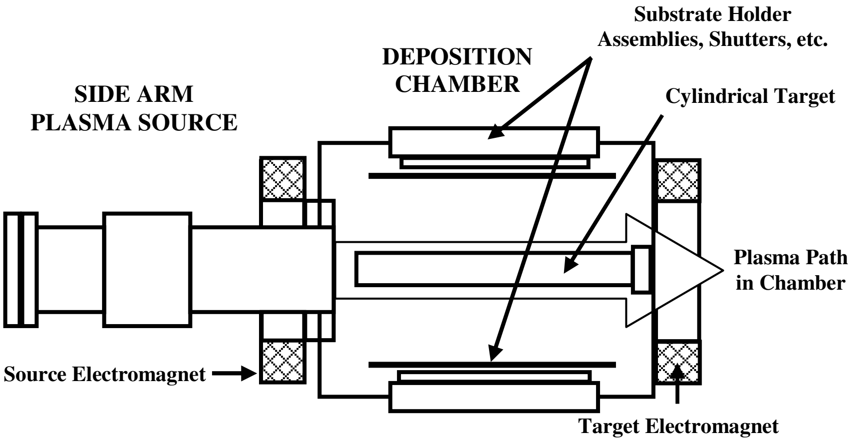
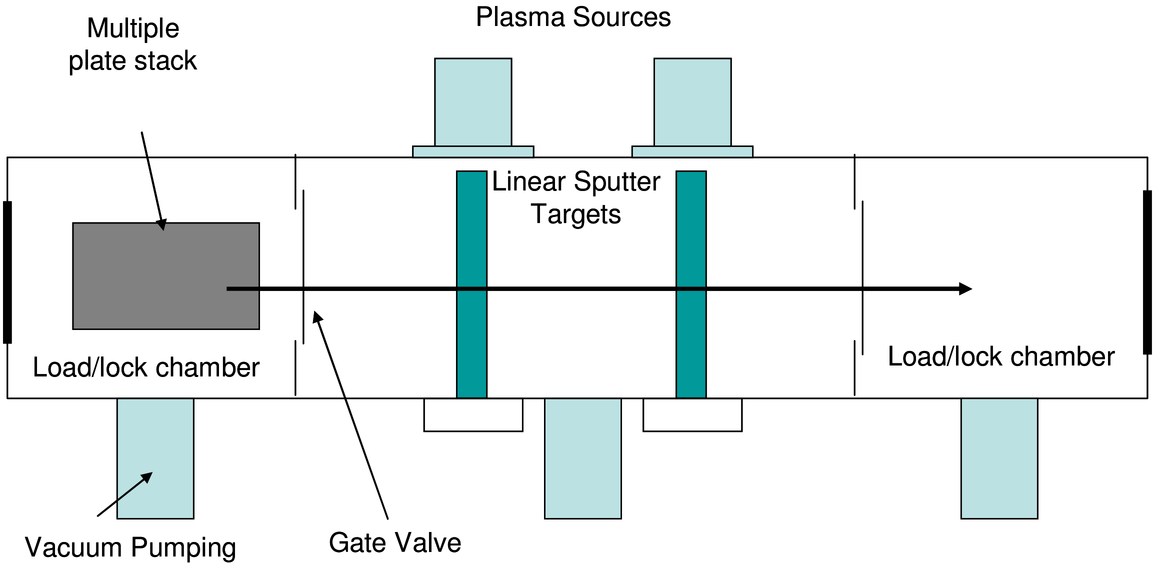


Figure D.3

Schematics of PQL 'Linear Target' Sputter Deposition System



(a) Cross section at target.



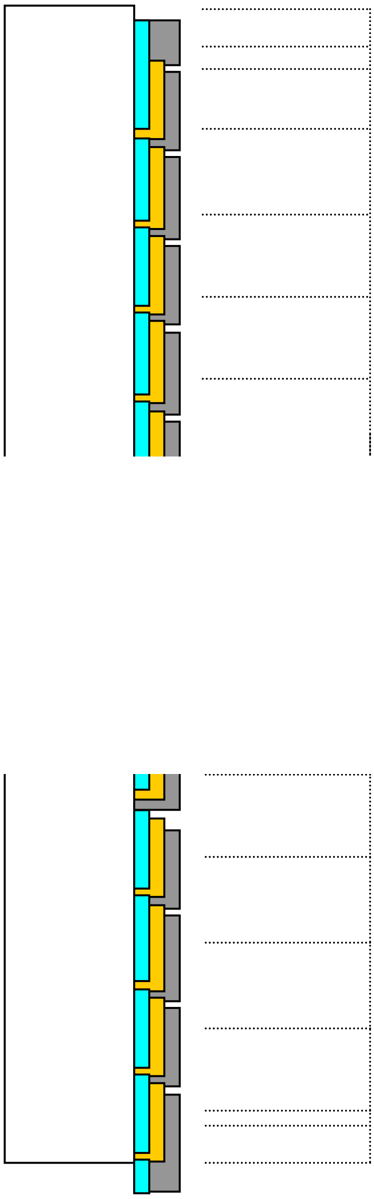
Two layer sequential coating; 800 off nom. 6'x2' panels per 8 hour shift

(b) Longitudinal section of two target system.

Figure E.1

Outline Monolithic Integration Schematic for a-Si based Solar PV Panel

A. Along panel width (0.66m dimension)



B. Across panel length (1.30m dimension)

Figure E.2
First Design (Vertical Processing) Laser Tool Schematic

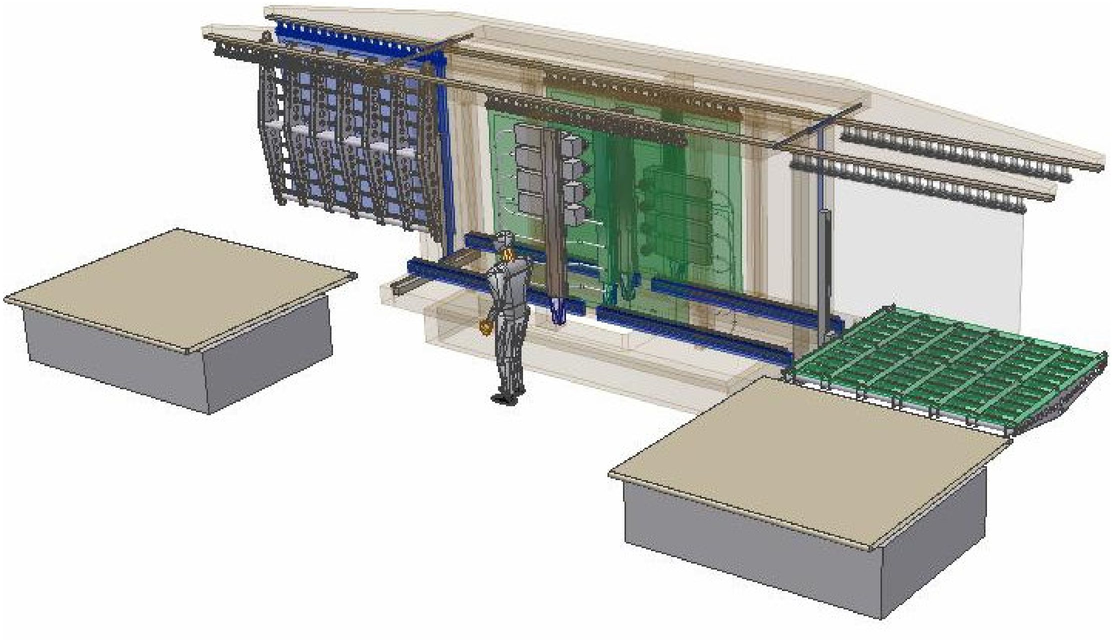


Figure E.3
Second Design (Horizontal Bed) Laser Tool Schematic