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LIFE Delivery Plan

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Overview of the LIFE Delivery Plan

Introduction

The LIFE Delivery Plan describes the path from ignition on NIF to achieving the goal of an operational fusion power plant that demonstrates all the functions and performance characteristics required to underwrite the move to a commercial fleet.

The Delivery Plan has been assembled based on the following principles:

- Ensure integration of technical development activity across all aspects of plant construction, technology demonstration and licensing.
- Constrain delivery by likely capability and capacity of partners and vendors, but not by funding availability
- Assume project starts after the demonstration of Ignition on the NIF
- Make use of available technologies, processes, materials and scientific performance wherever possible, including demonstration of the fusion target solution on the NIF
- Determine the scope, timescale and cost of tasks by consultation with vendors wherever possible
- Project execution to meet the highest standards of technical rigor and scrutiny – quantifying technology progression and risk, and utilizing stage gates and clear metrics to align decision making and key investment decision points
- Technology progression to follow the accepted evolution from conceptual to preliminary and final design, with component testing, benchtop integration, prototyping, and demonstration phases for key sub-systems (quantified according to the DoD Technology Readiness Levels).
- Schedule set by the ability of benchtop data to constrain the plant design envelope and to define interfaces between sub-systems and the plant. Final designs of line replaceable units to be set by prototyping and offline demonstration testing.
- Delivery assumed to make full use of the vendor base and national laboratory / academic capability

With effective systems engineering and interface management, the Pilot Plant structures and conventional systems can be designed and built, while preserving significant margin for final adjustments to process parameters, such as laser energy, repetition rate and fusion chamber design. This approach to scheduling and delivery is made possible by the modular nature of the LIFE design. This enables a single step pathway from NIF to integrated fusion demonstration. A pilot facility can be built that is capable of subscale qualification testing of materials and processes and that is able to be scaled to full commercial operations.

The Delivery Plan itself is organized around a set of key technical, operational and regulatory issues to be resolved and demonstrated in order to deliver commercial fusion energy. Each issue is ranked in importance and is assigned a relative risk and technical readiness level (TRL). Criteria are defined that align with key investment decision points in the Pilot Plant project. These criteria, when met, progressively reduce risk and increase technical readiness toward the ultimate goal of demonstrating commercial viability. Appendix A summarizes the key technical issues and stage-gate criteria. Appendix B has a summary of the corresponding technical risk assessment.

Delivery Plan

The delivery plan development process and relationship between various key project documents is illustrated in Figure 1.

Figure 1: Delivery Plan development process

The scope of the delivery plan is described in terms of four major activities (Figure 2):

- Pilot Plant Project
- Sub-system technical Demonstration and Risk Reduction
- Licensing and Regulatory framework
- Vendor Engagement

Each of the activities has its own logical flow and interfaces with the other activities. It's the interfaces that define the balance between technical risk and time to market. If the plan is too serial, the schedule stretches and the business case fades. If the plan is too parallel, technical risk is excessive. Figure 3 shows an overall delivery schedule that strikes a sensible balance between technical risk and time-to-market.

Figure 2: Primary delivery plan activities

Figure 3: Indicative delivery schedule

LIFE delivery commences with initiation of Pilot Plant conceptual design. In parallel, laboratory and small scale testing are used to validate computational models and establish feasibility for constituent technologies. Testing on NIF drives development and validation of the LIFE prototype fusion target. Design and construction of major test facilities begins in preparation for testing of full, and near full scale equipment.

Licensing efforts focus on defining the licensing strategy and preparing the license application. A notice of intent is generated and the NEPA process is initiated. Waste streams are assessed and alternate disposition pathways identified. Vendor engagement in key long-lead areas is initiated: laser diodes, deuterated KDP, fusion engine structural materials, fusion targets, power conversion and heat transfer systems. The acquisition strategy for the Pilot Plant design and construction services is developed.

Approximately 2 years from Project start, preliminary design of the Pilot Plant begins. Site selection activities should be nearing completion by this point. Risk reduction activities shift from small scale testing to full scale or near full scale components and systems. A full scale laser beam line is tested. Plant scalable fusion engine and tritium separation equipment are tested. Interface design freezes for most special process equipment are 1 to 2 years after start of preliminary design. An integrated fusion target manufacturing pilot line is built and used to deliver prototype targets to NIF for tolerance and margin testing.

The Pilot Plant license application is submitted in 2 to 3 years from Project start. LIFE staff will work with regulatory agency staff to complete review of the license application. This process is supported by separate effects and integral testing of LIFE safety significant equipment. By the time that power block construction begins, ~6 years from Project start, manufacturers for process equipment have been selected. Procurement packages for laser system line-replaceable units are released. First article Plant hardware is undergoing qualification testing. The industrial partner, who will design, build and operate the fusion target pilot plant, is selected and the fusion target pilot plant design work gets underway.

Plant construction and equipment installation and commissioning are expected to be completed ~12 years from Project start. A license that authorizes qualification testing is needed by this point. We anticipate 6 to 12 months of systems commissioning using inert targets. This is followed by 1 to 2 years of burst-mode testing with live targets. Continuous fusion operations commence within 18 to 36 months. The Pilot Plant is designed to enable testing of both subscale and full scale fusion engine equipment.

The pace of scale up will be dictated by the rate of technical progress and progress toward establishing the operational basis to support an NRC license for commercial operations. The Plant will be capable of delivering electricity to the grid once continuous fusion operations commence. Electricity production campaigns will be conducted to build confidence and prepare the way for full commercial operations.

Transition to commercial operations will be based on multi-thousand-hour demonstrated safe and secure fusion operations and the ability to obtain an NRC license that authorizes commercial operations. The goal is to have sufficient component reliability and maintainability to support greater

than 70% plant availability during initial commercial operations. By this point, the Pilot Plant should be capable of delivering about 400 MWe to the grid.

Based on current analysis of the delivery plan, the technical risk reduction activities are calculated to require 200-300 M\$ dollars per year for a period of about seven years, with a transition in the later years to pilot plant detailed design and construction.

Summary

The LIFE Delivery Plan charts a path from ignition on NIF to commercial fusion. The plan calls for a set of risk reduction development activities integrated with construction and licensing of the LIFE pilot power plant. The plan structures these activities with clear metrics and criteria aligned with key investment decision points. A risk assessment of this Plan provides a basis for investors to make calibrated evaluations of technical progress and residual risk as the Project proceeds (See Appendix B).

The concurrent approach is made possible by the modular nature of the LIFE design. With proper systems engineering and interface management, the Pilot Plant structures and conventional systems can be designed and built, yet preserving significant margin for final adjustments to process parameters, such as laser energy, repetition rate and fusion chamber design.

This approach enables a single step pathway from NIF to commercial fusion demonstration. A pilot facility can be built that is capable of subscale qualification testing of materials and processes but that can be scaled to full commercial operations. The commissioning pathway for this facility follows that required for any integrated fusion facility. Its ability to be up-rated to full scale operations represents a substantial saving in cost, time and delivery risk.

A set of key technical issues that require resolution in order to deliver commercial fusion energy has been identified. These issues, combined with stage-gate criteria and current levels of technical readiness, were used as a basis to define the work scope and resources needed to resolve the issues.

This paper only presents a top-level overview of the requirements and solution pathway. Further detail is available on request, subject to proprietary information control.

Appendix A

Key Technical Issues and Stage-Gate Completion Criteria

During 2010, an extensive Delivery Plan development exercise was conducted. A functional work breakdown structure of the LIFE Plant was developed, containing 380 elements to serve as a comprehensive functional description of a LIFE power plant. 42 work packages were prepared, resulting in the identification of 470 functional requirements. 970 work statements were developed and 185 milestones. This plan was integrated into a 250-element delivery schedule. Technology delivery timescales and costs were derived in consultation with over 30 vendors, and experience with the NIF and other projects.

This database yielded a set of key technical issues to be resolved and demonstrated in order to deliver commercial fusion energy. Each issue was ranked according to its impact, were it not to be resolved, and assigned a TRL using the US Department of Defense definitions for technical readiness.

The delivery plan is divided into three top-level phases that represent substantial steps in project maturity. Stage-gates are used to separate the phases, with a quantified set of completion criteria that must be met in order to move to the next stage.

A summary of key technical issues and stage-gate completion criteria are specified below for each of the major topical areas. This list is intended to provide an indicative guide as to the delivery plan structure. Stage gates in different areas of the project (construction, long-lead procurement items, line-replaceable units, etc) would of course be timed separately.

The issues are separated into the following areas: Fusion Physics, Target Manufacturing, Tritium Fuel Cycle, Target Injection and Tracking, Laser Driver, Fusion Engine, Power Conversion, Licensing and Regulatory, and Integrated Site Operations.

Fusion Physics

Key Technical Issues:

- Reliable, on-the-fly ignition with gain ~60
- Target materials compatible with other elements of LIFE process and regulatory constraints

SG1 Criteria:

- Projected performance meets economic criteria, materials of construction compatible with laser propagation, debris management, waste disposal, mass manufacturing and tritium processing
- Optical analysis of laser beam delivery verifies that LEH opening, including plasma closure and hohlraum location uncertainty, is adequate for beams to clear the LEH
- Systems analysis defines shot-to-shot tolerance on fusion yield

- Demonstrated gain and yield on NIF scales to Point Design gain and yield at Point Design laser energy

SG2 Criteria:

- Demonstrated gain and yield on NIF scales to Point Design gain and yield at Point Design laser energy: Target fabricated using processes that can be scaled to mass manufacturing
- Target ignition tolerances measured on NIF: laser beam spatial tolerance, manufacturing tolerances, material specifications, tolerance to failed beams
- Demonstrated capability to reliably ignite targets on NIF. Yield, gain and margin within Point Design tolerances.
- Laboratory level demonstration of ability to repeatedly hit targets with accuracy required for ignition

SG3 Criteria:

- Sustained, continuous fusion operations: on-the-fly ignition at >99% reliability within Point Design tolerances on gain and yield
- Demonstrated ability to reliably ignite targets fabricated from recycled tritium and plant prototypic target materials; including any recycled target materials

Target Manufacturing

Key Technical Issues:

- Producing in-spec deuterium-tritium layer in a production environment
- Target survival during injection and flight
- Mass manufacture of targets: 500M/yr for each plant at <\$1/target
- Minimize tritium inventory associated with target filling operations (consistent with <8 hours storage)

SG1 Criteria:

- LIFE target manufacturing process flow-sheet defined: unit operations, mass and energy balances
 - Meets economic criteria
 - Materials compatible with laser propagation, debris management, and waste disposal (basis is analysis and laboratory scale tests)
- Capability to fabricate a representative LIFE Point Design target

- Procurement strategy for LIFE targets defined

SG2 Criteria:

- All unit operations demonstrated to reliably meet target manufacturing tolerances
- Models used to calculate target mechanical and thermal survival during injection verified by separate effects testing
- Demonstrated gain and yield on NIF scales to Point Design gain and yield at Point Design laser energy: Target fabricated using processes that can be scaled to mass manufacturing
- Contractor selected to design, build and operate target manufacturing pilot line
- Disposition strategy for target waste/recycle streams defined

SG3 Criteria:

- Demonstrated capability to manufacture targets at Point Design rate ~300M/yr
 - Recycled tritium and target materials (if applicable)
- Demonstrated target cost scalable to Point Design cost in a commercial plant at full production rate
- Demonstrate acceptable system availability
 - Availability specification for first commercial operations >70%
 - Target manufacturing availability allocation >97%
- Demonstrated ability to safely contain tritium and reliably conduct target filling and staging operations within tritium inventory requirement
- Target waste streams meet applicable state, federal and local criteria for storage and disposal
 - No streams to exceed criteria for shallow land burial

Tritium Fuel Cycle

Key Technical Issues:

- Tritium breeding ratio adequate for self-sufficiency and startup of new plants
- Recovery of tritium from coolant/breeder and chamber exhaust gas

SG1 Criteria:

- Tritium fuel cycle process flow-sheet defined: unit operations, mass and energy balances, chemical composition of process streams including specifications on impurities

- Meets tritium inventory requirements
- TBR validated by detailed analysis
- Provide experimental evidence to support feasibility of extraction of tritium from coolant/breeder material, recovery of tritium from chamber exhaust gas and acceptable levels of containment and system holdup

SG2 Criteria:

- Demonstrated capability to recover tritium from coolant/breeder using plant scalable components (surrogates may be acceptable)
 - E.g. Centrifugal contactors, plant scale electrolysis
 - Materials compatibility, continuous operations
 - Safe operations with demonstrated tritium containment
- Demonstrated capability to recover tritium from chamber exhaust gas using plant scalable components (surrogates may be acceptable) at required separation efficiency and with acceptable cross-contamination.
 - Materials compatibility, solubility and permeability
 - Continuous operations
 - Safe operations with demonstrated tritium containment
- Demonstrated performance of TCAPS (or equivalent) technology using chemical composition of streams expected from LIFE
- Concepts of operations and maintenance for tritium systems defined

SG3 Criteria:

- Demonstrated tritium self-sufficiency
- Demonstrated capability to maintain tritium inventory below licensing limit
- Demonstrate acceptable system availability
 - Availability specification for first commercial operations >70%
 - Tritium processing availability allocation >97%
- Demonstrated capability to maintain system and replace components in a production environment

- Demonstrated safe operations and capability to keep tritium release below licensing limits.

Target Injection and Tracking

Key Technical Issues:

- Accurate, reliable, repeatable injection in a fusion environment
- Target tracking in fusion environment
- Injector availability
- Injection without excessive mechanical or thermal loads on targets

SG1 Criteria:

- Demonstrated capability to inject surrogate targets at Point Design repetition rate and accuracy (burst-mode, ~ 1 minute)
 - Demonstrate feasibility of maintaining target integrity and cryogenic environment
- Demonstrated capability to track surrogate targets with required level of accuracy at Point Design repetition rate (burst mode, ~ 1 minute)
- Demonstrated capability to engage surrogate targets at Point Design repetition rate and accuracy (burst-mode, ~ 1 minute)
 - Low power lasers, 3 spots inside hohlraum (2 outer ring, 1 inner)

SG2 Criteria:

- Demonstrated capability to inject surrogate targets at Point Design repetition rate and accuracy (burst-mode, ~ 1 hour)
 - Plant scalable hardware, cryogenic
- Demonstrated capability to track surrogate targets with required level of accuracy at Point Design repetition rate (burst mode, ~ 1 hour)
 - Plant scalable hardware
- Demonstrated capability to engage surrogate targets at Point Design repetition rate and accuracy (burst-mode, ~ 1 hour)
 - Beam steering at laser front end
 - Prototypic beam transport system

SG3 Criteria Transition:

- Demonstrated capability to inject, track and hit targets on the fly with >99% reliability

- Demonstrate acceptable system availability (>97%)
 - Availability specification for first commercial operations >70%
 - Target injection and tracking availability allocation >97%
 - Injector and tracking system reliability in a fusion environment (radiation, EMP, vibration, etc)
 - Cassette-based injector replacements

Laser Driver

Key Technical Issues:

- High average power operation at adequate electrical efficiency
- Focal spot consistent with laser entrance hole opening in hohlraum – including target tilt tolerance and plasma closure effects
- Final optic survival
- Target engagement
- Laser system availability

SG1 Criteria:

- Conceptual level plant laser system design complete. Meets economic, operational and maintainability requirements.
- Plant laser system optical damage projections calibrated to subscale optics damage test data
- Selected component level demonstrations, scalable to Point Design performance
- Verification of Point Design chamber clearing ratio: based on Laboratory scale laser beam propagation testing

SG2 Criteria:

- Demonstrate Point Design performance in a full scale beam line
 - Continuous high average power operation
 - Wall-plug efficiency
 - Thermal management
 - Optical damage at full scale
 - Frequency conversion efficiency

- Demonstrate fast pointing of laser beam to Point Design level of accuracy, demonstrate vibration isolation and compensation
- Demonstrate final optic change out in laboratory environment
- Demonstrate Point Design focal spot at TCC distance
- Diode cost >10x Point Design value scalable to Point Design cost

SG3 Criteria:

- Demonstrate Point Design laser performance in a fusion environment
 - >97% system availability
 - Reliable operation in fusion EMP, vibration environment
 - Hot-swap maintenance, autonomous startup
 - >99% reliable target engagement
 - Reliable clearance of LEH
- Demonstrate final optic performance and survival in fusion environment: thermal management, pressure pulse, debris, radiation, maintenance
- Full commercial manufacture of laser beam boxes

Fusion Engine

Key Technical Issues:

- Fusion chamber survival: material lifetime in fusion environment, corrosion, thermal and mechanical insults
- Chamber clearing and fusion debris management
- Lithium loop heat transfer and corrosion
- Fusion chamber design consistent with fabrication processes
- Concept of chamber replacement
- Overall system availability
- Production capability for chamber structural materials

SG1 Criteria:

- Fusion engine engineering design package produced
 - Mechanical design, heat transfer system, interface with Rankine cycle

- Self-consistent thermal stress, radiation damage, thermal fatigue, chemical compatibility constraints
- Fabrication and assembly process defined
- Operational feasibility of coolant / breeder performance consistent with established material properties
- Kilogram level batches of engine structural materials manufactured with acceptable composition

SG2 Criteria:

- Fabrication and successful testing of scalable fusion engine components: fusion chamber segments, pumps, heat exchangers, tritium recovery equipment
- Demonstrated chemical compatibility with lithium and plasma facing environment: scalable component tests
 - Lithium with expected impurity composition
- Successful fabrication of fusion engine structural materials at multi-ton scale
- Remote handling demonstrated on full-scale non-rad components

SG3 Criteria:

- Demonstrate continuous fusion operations
 - First wall lifetime >1 full power year
 - Safe operation, tritium containment, tritium inventory within licensing requirements
 - Acceptable vibration levels
 - Integration with Rankine cycle
 - Fusion engine availability >85% (plant availability >70%)
 - Chamber clearing and fusion debris recovery
- Demonstrate maintenance operations
 - Remote handling
 - Chamber coolant connection make/break in production environment
 - Maintenance equipment survival in radiation environment
 - Full commercial manufacturing of fusion engine structural materials
- Waste streams meet state, local and federal requirements
- Safe conduct of startup, shutdown , maintenance and off-normal operations

Power Conversion

Key Technical Issues:

- Integration of Rankine cycle with fusion source – mitigating the potential for lithium water reactions, tritium release through Rankine cycle

SG1 Criteria:

- Design of the LIFE Rankine cycle
 - Integration with lithium heat transfer system
- Tritium containment design consistent with Rankine cycle
- Select vendors to partner in the design and delivery of power conversion system for pilot plant

SG2 Criteria:

- Experimental validation of models used to assess tritium containment from Rankine cycle
- Fully integrated design for power conversion cycle and fusion engine

SG3 Criteria:

- Demonstrated integration with LIFE engine
 - Continuous fusion operations
 - Startup, shutdown, operational transients
- Demonstrate acceptable system availability (>97%)
- Demonstrate tritium containment within licensing requirements

Licensing and Regulatory

Key Technical Issues:

- Licensing strategy
- NRC license for initial operations
- NRC license for commercial operations
- Regulatory approval of waste streams

SG1 Criteria:

- Preliminary hazards analysis complete
 - Design basis accidents defined
 - Safety significant systems and structures identified
 - Engineered controls specified

- Safety R&D requirements specified
- Licensing strategy defined
- NEPA process for site selection complete

SG2 Criteria:

- NRC issues favorable safety evaluation report
- Site selection

SG3 Criteria:

- Demonstrated capability to conduct continuous fusion operations safely and securely
 - Startup, shutdown, operational transients
 - Maintenance operations
 - Tritium containment and inventory within licensing limits
 - Waste streams and operational releases within licensing limits
- Demonstrate ability of safety related materials and structures to operate safely in fusion environment
 - Radiation damage
 - Thermal stress, fatigue, chemical corrosion, etc
 - Multiple plant lifecycles
- Transition from license authorizing test operations to NRC license

Integrated Site Operations

Key Technical Issues:

- Concept of operations
- Concept of maintenance
- Personnel requirements

SG1 Criteria:

- Concept of operations and maintenance requirements document complete. Identifies operations and maintenance activities. Estimates staffing levels and specifies staff qualification requirements. Identifies requirements for specialized maintenance equipment.
- Quality requirements defined for plant operations and procurement of equipment.
- Detailed neutron activation calculations used to define radiation hardening requirements for remote handling equipment and storage requirements for activated components.
- Full site conceptual design completed

SG2 Criteria:

- Personnel training and qualification plans developed. Strategic plan in place for development of personnel supply chain needed to support LIFE power plant fleet.
- Prototypes of specialized maintenance equipment built and tested on plant scale or near plant scale hardware.
- Design requirements specified for operations simulator that will be used to train plant operations personnel.
- Final design completed for all construction activities

SG3 Criteria:

- Demonstrated safe and secure operations. Personnel exposure to radiation and other industrial hazards within regulatory limits.
- All maintenance operations demonstrated: fusion chamber replacement and remote disassembly, laser and final optic change out, rapid replacement of target injector.

Appendix B

Risk Assessment of Delivery Plan

Table B-1 summarizes the risk assessment. Key issues are summarized in parsed form. Potential impact associated with each issue is shown in the adjacent column.

High impact is defined as an issue that must be resolved or the project cannot proceed. Work-around is difficult or impossible. Medium impact is defined as having significant economic impact. Work-around impacts design of multiple WBS Level 2 elements. Low impact is defined as having modest economic impact. Work-around options exist if deemed necessary.

The colored columns in the table correspond to different Stage Gates in the delivery plan. The colors correspond to high, medium and low residual risk. To calculate residual risk associated with an issue, the issue impact is multiplied by the confidence level that the issue has been demonstrated as resolved. For example, under fusion physics, the issue identified as “Gain >60” is ranked as a medium impact issue; plant is viable over a range of fusion gains and lower gain can be compensated by increasing laser energy or repetition rate. Because ignition has yet to be demonstrated on the NIF, our current level of demonstration is low. The product of these two factors yields a high residual risk. However, to meet the SG1 criteria, ignition must be demonstrated on a scalable prototype of a LIFE target. Demonstration level goes from low to medium and residual risk from high to medium.

The risk assessment, combined with the stage-gate criteria, provides a basis for investors to make calibrated evaluations of technical progress and residual risk as the Project proceeds.

Issues		Consequence				
Fusion Physics			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Gain >60	M				
	On-the-fly ignition	H				
	> ~99% probability of ignition	M				
	Target materials compatibilities	H				
Fusion Targets			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	DT layer in production environment	H				
	Target survival: injection, flight	H				
	Mass manuf: 400M/yr, <\$1	H				
	Tritium Inventory-Target Filling	M				
Tritium Fuel Cycle			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Tritium Breeding Ratio	H				
	Recovery from Li	H				
	Recovery from Xe	H				
Target Injection and Tracking			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Accurate and repeatable in fusion env	H				
	Injector reliability in fusion env	M				
	Target survival in injector (fusion env)	H				
	Injector availability	M				
	Target tracking in fusion env	H				
Laser Fusion Driver			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Rep-rate operation	H				
	Final optic survival	H				
	Electrical efficiency	L				
	Target engagement	H				
	Focal spot consistent with LEH	H				
	Laser system availability	M				
Fusion Engine			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	First wall radiation damage survival (FMS) 10 dpa	H				
	First wall radiation damage survival (ODS) 50 dpa	M				
	Chamber clearing	H				
	Debris management-from chamber outlet	H				
	Heat Transport - from chamber outlet	M				
	Thermal and mechanical insults	H				
	Corrosion	M				
	Chamber Design consistent with Fabrication	M				
	Availability	M				
	Concept of chamber replacement	M				
	Production capability for Chamber Materials (FMS)	M				
	Production capability for Chamber Materials (ODS)	M				
Power Conversion Systems			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Tritium release through Rankine cycle	M				
Licensing and Regulatory			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Licensing strategy	H				
	Auth for initial ops	H				
	NRC license for ComOps	H				
	Regulator approval of waste streams	H				
Integrated Site Operations			Current	SG1 Criteria	SG2 Criteria	SG3 Criteria
	Concept of operations	M				
	Concept of maintenance	M				
	Personnel requirements	M				

Table B-1: Technical risk assessment summary