Managing Big Science Projects: Avoiding the Near Death Experience

Many large science projects experience serious cost and schedule overruns. These frequently lead to cancellation or to the near-death experience of being reorganized and replanned. This talk will describe the cultural contrasts between scientific research and the culture of big projects. It will define the ideal linear project and the perspectives and techniques needed to manage such a project. Finally, it will survey the real world complexities that make nearly all projects more complex and strategies to deal with these complexities. Examples of these techniques will be drawn from high-energy physics projects, LIGO and the Thirty Meter Telescope project.
LIGO – a centralized scientific tool

Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

Livingston Observatory
Louisiana
One interferometer (4km)
The near death experience lurks...

- Too many large scientific projects get into trouble
  - Trouble is diagnosed at vulnerable times
  - Projects are frequently reorganized
  - Some projects are canceled or they fail

- The review-cry-coach-review-cry-coach-fire-reorganize-review... cycle as a learning tool
  - There has to be a better way

- Spread case-based experience of scientist/managers to those in emerging projects

- Make the scientist-specific cultural setting visible
This Talk

- Culture
- Big science is different from small science
- Management goals in big science
- The linear project
- Complex projects
- Structuring the linear project
- New kinds of projects
Sociology
The Astronomer - Vermeer
The Geographer - Vermeer
The Collaborators – A Caltech forgery
<table>
<thead>
<tr>
<th><strong>UBIQUITOUS EXPERTISES</strong></th>
<th>(Harry Collins et al., Cardiff)</th>
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<th><strong>DISPOSITIONS</strong></th>
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<td>Interactive Ability</td>
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<td>Beer-mat Knowledge</td>
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<td>Primary Source Knowledge</td>
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<td>Contributory Expertise</td>
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<td>(Transmuted expertises)</td>
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<td>Ubiquitous Discrimination</td>
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<td>Downward Discrimination</td>
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<td>Referred Expertise</td>
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<tr>
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<tr>
<td>Experience</td>
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Expertises — Harry Collins

- **Contributory expertise** — the knowledge that enables a participant to advance a field

- **Interactional expertise** — knowledge sufficient to understand the subject matter of a field and to support communicating intelligently with contributory experts in the field

- **Referred expertise** — Expertise of a contributory or interactional nature in one field that is applied usefully in a new field
Interacting in little circles

- Lone researcher
- Tacit knowledge
- Community and shared history
- Expertise narrowly defined

Contributory expertise
Collaborators

Lone researcher 1
Tacit knowledge
Community and shared history
Expertise narrowly defined

Lone researcher 2
Tacit knowledge
Community and shared history
Expertise narrowly defined

Contributory expertise
Projects

Lone Project Manager
Tacit knowledge
Community and shared history
Expertise narrowly defined

Lone researcher
Tacit knowledge
Community and shared history
Expertise narrowly defined

Lone engineer
Tacit knowledge
Community and shared history
Expertise narrowly defined

Contributory expertise
Project Science as a culture

- Theoretical scientists
- Experimental scientists
- Project scientists

Three distinct cultures and temperaments
Three distinct expertises
Project Management and Management of Operating Organizations

- Project management
- Operating management

Two distinct cultures, temperaments, expertises and management goals
This is the bare minimum budget I need for my project.

What could you do with half this amount?

Fail.

When can you start?

I think I just did.
The training and filtering of scientists

- **Undergraduate study** – reading and problem sets
  - Selects productive problem solvers
- **Graduate study** – *Apprentice* research under an advisor
  - Absorb the advisor’s techniques and values
- **Early postdoctoral career** – *Independent contributor* to research
  - Show independence, innovation, creativity, analytical and technical mastery, focus, teaming in small teams
- **Midcareer** – *Mentor* in research
  - Confidence, mastery, emergence as a leader in a research field, strong focus, tenacious, competitive, seeker of truth
Work-motivation of scientists

- Among the most stable of work-motivations throughout one’s career* are the need for:
  - Achievement
  - Affiliation
  - Power

- The selection process for scientists prefers achievement

- Big science requires teams and members who value affiliation and power

* McClelland, D., Motives, Personality and Society, New York: Praeger 1984
Work motivation mapping

- Achievement
- Power
- Affiliation
The project manager’s motto – the project mindset

"le mieux est l'ennemi du bien."  
Voltaire, 1764

"Il meglio è l'inimico del bene."  
– Boccaccio, 14th century

"The better is the enemy of the good enough."
## Small Science vs. Big Science

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<tr>
<th>Attribute</th>
<th>Small Science</th>
<th>Big Science</th>
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<tbody>
<tr>
<td>Decisions made by</td>
<td>scientists, creators, inventors</td>
<td>managers, directors, delegated</td>
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<tr>
<td>Design flexibility</td>
<td>flexible, creative</td>
<td>fixed, baselined</td>
</tr>
<tr>
<td>Fabricated by</td>
<td>in-house craftwork, &quot;make&quot;</td>
<td>industrial approach, &quot;buy&quot;</td>
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<tr>
<td>Team composition</td>
<td>predominantly scientists</td>
<td>scientists, engineers, accountants, PMs</td>
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<tr>
<td>Visibility of</td>
<td>private</td>
<td>public</td>
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<tr>
<td>project</td>
<td></td>
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<tr>
<td>Project process</td>
<td>opaque</td>
<td>transparent</td>
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<tr>
<td>Success defined by</td>
<td>scientists, creators, inventors, peers</td>
<td>managers, reviewers, sponsors, peers</td>
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From discussions with Harry Collins
Big science is public

- Everything about the conduct of big science must be transparent to the public
- This is an ethical imperative
  - You are consuming resources that could make a difference to:
    - The public
    - Other recipients of the private support
    - Other scientific opportunities
- Your project's resources are not an entitlement
- You must be prepared to be on 60 Minutes
The Linear Project
The Linear Project: An Ideal

- Before we can create and manage a real world project we must be able to isolate the ideal project inside the real project.
- What are the identifying features of the ideal project?
  - The project that can be managed in a straightforward manner.
The Linear Project

Executing the project consists solely of carrying out a well defined plan

- Project goals and requirements are stable
- Sponsor support and funding are stable
- Managing institutions do not confuse the goal of project success with their other goals
- Resources are matched to project
- Resources are really controlled in one project office
- Project team owns the plan

The result is that the major risks are technical
  - Remaining risks are inexperience and human behavior
Managing complex (nonlinear) projects

- Most real world projects are not linear projects
- Nonlinear projects are managed with great management attention to nonlinear attributes
  - Diffuse goals steered towards project goal
  - Multiple resource bases coordinated through negotiation and consensus building rather than real control
  - Project replanning places heavy burden on leadership and erodes focus on and respect for project plan
  - Project is distracted by reinventing and rejustifying itself
Managing complex (nonlinear) projects

- Most nonlinear projects are managed without reference to a simple linear plan
  - How it could be
  - The most important things that should be managed for project success are the linear attributes
  - Nonlinear aspects are taken for granted and an accommodation is made and not seen as a complication
  - This accommodation is a slippery slope

- Projects must strive to achieve a linear model as much as possible in order to minimize risk
Generic nonlinearities/complications...

- Major project replanning is caused by:
  - Project goals unstable
  - Politics interfere with project progress
    • project either follows politics or
    • tries to operate adaptively in the lee of the political winds
  - Sponsor attention or support varies within term of project
  - Annual funding does not follow either:
    • funding profile dictated by technical pace of project or
    • funding profile agreed to in a funding limited plan
Generic nonlinearities/complications...

- Institutional setting of project poor
  - Operating laboratory management imperatives influence decision making, resource allocation, funds management
    - Project managers create, execute, dismantle
    - Operating lab managers conserve and adjust
    - Transient vs. continuous management
  - Host institutional culture and support infrastructure not matched to project
  - Institutional setting fragmented among disparate institutions
Generic nonlinearities/complications...

- Project team members suffer cultural mismatch
  - traditional small science vs. big science gap
  - values system not matched to project science
    - project science not matched to traditional graduate student education, nor to tenure evaluation process
    - projects are successful because the contributions of many types of team members are combined, thus contributions must be matched to project needs and not just to academic meritocracy
  - team members do not respect the systems and processes of large projects
  - dysfunctional information sharing, information structure
    - Promotes fragmentation into small islands or stovepipes, often along scientist/nonscientist lines
...Generic nonlinearities/complications

- Resources management decentralized
  - European model with independent institutes each controlling own budget and resources
- Scientific creativity without formal change management
- Project unable to heal or to confront surprise
Organizing the Linear Project
Organizing the Linear Project

- Project stages
- Baseline
- Work Breakdown Structure (WBS)
- Organization
- Cost Estimate and Risk
- Schedule
- Performance Measurement
Distinct stages in a project...

- Definition to Reference Design
- Reference Design to Baseline Definition
- ...to Final Design and Commitment
- ... to Industrialization
- Execution and Performance Measurement
- Integration and Plan to Completion
- Endgame

Manage obligations
Manage costs

*broke and done on the same day*
The baseline...

- Scientific requirements are defined and fixed
- Technical requirements meet the scientific requirements and are fixed
- Project deliverable is defined in a conceptual design
- Subsystems are defined
  - interfaces are defined
- Work Breakdown Structure (WBS) defines all work to be performed in the project including delivery of each subsystem and their integration
The baseline

- Costs are estimated at the lowest level in the WBS
- Schedule is developed following the WBS
- Costs and other resources are integrated with the schedule to define the value of each scheduled activity, and a profile of obligations and costs
- Risks are assessed at the cost estimate level in the WBS and a contingency pool of funds are defined for project-wide management of risks
- Basis for performance measurement is established
When to start defining the baseline?

- On day 1 with pencil sketch?
- ...
- After conceptual reference design defined?
- ...
- When sponsor makes full commitment?
- ...
- At Final Design Review?
- ...
- When as-built drawings are completed?
When to baseline?

- This question is very much misunderstood
- Don’t delay
  - This leads to irresponsible softness in project team commitment to the reference design
  - After all, we aren’t baselined yet, so…
Reference Design to Baseline Definition

- Put reference design under early configuration control as interim baseline
  - Grow a culture of disciplined work that fosters commitment to timely decisions
    - Team commits to strawman
    - Team learns process of orderly change
    - Team learns that work can now move forward
    - Team learns hierarchy of technology options and design choices
      - Baseline choice with fallback option and decision date
      - Equal options with decision date
      - Firm baseline choice with no option
    - Sponsor must recognize what this is
Work Breakdown Structure (WBS)
Work Breakdown Structure (WBS)

- Tracker
  - Cryostat
  - Electronics
    - Readout
      - Front End Op Amp
  - Support Structure

- Calorimeter

- Muon Subsystem

- Solenoidal Magnet

- Project Management
  - Project Controls
  - System Engineering
  - Subcontracts
  - QA
  - ES&H
  - Documentation
Cost Estimate - Basis

- Establish detailed Work Breakdown Structure
- All estimating to be done "bottom up" by the engineers and scientists directly responsible for each item
  - scientist + engineer
- Establish a written Cost Estimating Plan that defines uniform formats and procedures for all estimators
- Each estimated item should have all information supporting the estimate for that item recorded in a standard Basis of Estimate worksheet for that item. The Basis sheet should be signed and dated by the estimator.
### ALMA Work Element Sheet

#### Task Information
- **Task Name**: Task Name
- **WBS Number**: TBD
- **Currency**: $ (or Euro, Yen, or PS (Pound Sterling))
- **Basis of Estimate**: EN (Engineering), VQ (Vendor Quote), PO (Place Order), or AC (Actual Cost)
- **Technical Risk Multiplier**: 2
- **Cost Risk Multiplier**: 1
- **Schedule Risk Multiplier**: 2
- **Calc. Contingency**: 34%

#### Labor Information
- **Name or Position**: (Text for the WBS dictionary)
- **Grade (years)**: 1, 2, 3, 4, 5
- **Staff (FTE's)**:
- **Labor Total (CY2000 dollars, thousands, including indirect costs)**: 0 (in $K)

#### Labor Grades
- **1**: Secretary, administrative aide, support technician
- **2**: Engineer or programmer, Sr. scientist
- **3**: Staff scientist
- **4**: Top level managers & scientists
- **5**: Top level managers & scientists

#### Materials and Contracts
- **Material Description**: Parameterization, Units required, Spares, Total Units, Unit Cost (K), Subtotal
- **Parameterization Formula**: Formula

#### Parametric Variables
- **NAnt**: # of antennas
- **NSta**: # of antenna stations
- **NNut**: # of Nutator stations
- **NIF**: # of IF Bandwidths
- **NChan**: # of Correlator Channels
- **Dur**: Phase 2 Duration, yrs
- **NR**: Non-recurring cost

#### Additional Parametric Variables
## GEM Cost Estimate Summary

**FY93 U.S. Dollars**

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<th>Description</th>
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<th>Maniflours</th>
<th>Labor, $</th>
<th>M + L, $</th>
<th>Markup, $</th>
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Project Science
## Gem Cost Estimate Details

**04/27/1993**

### Vessel Support Structures Fab/Assy

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<td>Ovfr Site Inspections</td>
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<td></td>
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<td></td>
<td>INSPAD 60 147 441 8,859 26,079 26,576</td>
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**SUBTOTAL - 40.03.1.2.3 Vessel Support Structures Fab/Assy**

**$2,295,819**

PRIME CONTRACTOR MARKUP 7.1% **$180,373**

CONTINGENCY 22.0% **$554,508**

**COST PLUS CONTINGENCY $3,674,998**

### Cost Matrix

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<tr>
<th>LABOR MATERIAL</th>
<th>ENO/DES</th>
<th>M&amp;S</th>
<th>INSP/ADM</th>
<th>PROC/FAB</th>
<th>ASSMBLY</th>
<th>INSTALL</th>
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<tbody>
<tr>
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<td>48,805</td>
<td>44,297</td>
<td>0</td>
<td>2,247,015</td>
<td>0</td>
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<tr>
<td>TOTAL $</td>
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<td>48,805</td>
<td>44,297</td>
<td>2,247,015</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>

### Labor Risk

- Technical Risk: 6%
- Cost Risk: 8%
- Schedule Risk: 8%

**TOUGH LABOR = EDIA LABOR = $44,297**

**Date of Estimate:** 06/15/92

**Estimator:** G. DeGu, Bowers
Element Scope:  This element includes all of the hardware required to physically support the coil, vessel, and muon sector assemblies in the underground hall. This will include the saddles to support the outer vessel as well as any jacking hardware provided to align the magnet, to compensate for ground motion, or to move the magnet assemblies.  This does not include any concrete structures, such as piers or support beams, which are assumed to be parts of the hall facility.

Technical design description:
The saddle support structures are low carbon steel weldments consisting of large flat plate sections.  Four saddle weldments are provided to support each vessel assembly, including the magnet and all internal detectors.  Total weight supported by four saddle supports is conservatively 3000 tons.

It is assumed that all four saddles see equal dead loads and horizontal loads.

All saddles can be hydraulically jacked to transport the vessel system and for alignment.  The jacking system is part of the transporter, and will be capable of lifting the weight of the vessel system plus the saddles, and have sufficient control to enable pitch, roll and elevation positioning.

Interface to the building foundation is through shim blocks mounted to the floor.

Total weight of four saddle support weldments is 121 tons

Two sets of four are required, one set for each vessel.

**Inspection/AsmIn**

Basis:

<table>
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<th>Service</th>
<th>Basis</th>
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<td>coordinator support during construction</td>
<td>3 mm</td>
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<tr>
<td>off-site/on-site inspections</td>
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</table>

**EDIA/OA Material&Services**

Basis:  Quality Assurance weld inspection time .5my

**Procurement/Fabrication**

Basis:  each vessel raw materials
saddles:  121 tons 304L stainless steel in finished structures
add 8% waste giving 131 tons of raw material
mill rate = $2.00/ lb yielding $262K

support blocks:  40 tons 304L stainless steel in finished structures
mill rate = $2.00/ lb yielding $80K

weld material cost is included in welding cost
transportation $2500/load x 10 loads = $25k
plate section burnig 0.5 days/ section, $600/ section x 60 sections = $36k
machine base plate 2 days/ weldment x 4 weldments = 8 days = $7k
weld fixtureing and alignment $20k
welding $10k per weldment x 4 weldments = $40k
blasting $25k per weldment x 8 weldments = $200k
rigging $50k
total cost per vessel= $882k
total cost for two vessels = $1764k
Cost of hydraulic jacking system $200k
Cost of 24 transporter grease pads $200k

**Installation/Ass’y**

Material ($k): 2
Basis:  This is covered in WBS 40.02.3.2.1, 40.04.1.1 - Magnet Installation

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<tr>
<th>Unit type: ea</th>
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<tbody>
<tr>
<td>Estimate Type: BU</td>
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Risk Factors:

**Technical:**  2
- Basis:  Fabrication techniques are standard. Simple shapes and interfaces. Loose tolerances, common materials.

**Cost:**  4
- Basis:  Vendor quotes on hydraulics and bottom up construction factors for structural assemblies. Mill costs for steel will vary based on the state of the national economy at the time of construction.

**Schedule:**  8
- Basis:  If built in sections off site, will have minimal impact on vessel installation schedule.

Misc Comments:

Current assumptions of floor movement vary up to 15 cm up and down.
TMT. TEL. OPT. M1.55A. WARP - Segment Warping Harness

Fabrication

Start: Mar 2009  End: Dec 2009

Estimator: Larry Stepp, RJ Ponichone

WBS/Phase Dictionary

The warping harness is a device that allows the warping of the primary mirror segment (TMT. TEL. OPT. M1.55A) to change its figure. The warping harness is an integral part of a Segment Support Assembly (TMT. TEL. OPT. M1.55A). It does not include any external measurement devices used to measure segments in the warping harness. Note: The cost of the warping harness is included in the TMT. TEL. OPT. M1.55A.

WBS/Phase Description

The warping harness will engage motors to control the actuation of the warping harness. This will be done using 18 beam springs that will be attached to the center of the warping harness as shown in the figure. The beam springs will be held in place by a support structure.

Labor

The cost to fabricate the warping harness is included in the TMT. TEL. OPT. M1.55A.

Material

The material costs associated with the warping harness are included in the TMT. TEL. OPT. M1.55A.

Assembly labor for electrical connectors

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<th>Start Date</th>
<th>End Date</th>
<th>Units</th>
<th>U/M</th>
<th>Unit Cost</th>
<th>Labor Cost</th>
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Direct Material: $581,169

Material Subtotal: $1,264,209

Travel:

$1,668

Priced Estimating Data Report

Monday, September 11, 2006

TMT. BUS. CST. 06.774. REL01

TMT Program Confidential Data

Priced Estimating Data Report

TMT. BUS. CST. 06.774. REL01

Monday, September 11, 2006

TMT Program Confidential Data
TMT: INS AG. AO5 INT - Adaptive Optics Sequencer Integration and Test

INT - Integration and Test
Responsible Estimator: Brent Eliebrock
Estimate Date: 9/5/2005

Assemble BEG/POE/PFTS with CTRL and spare - 5 hr BW (28 days)
Acceptance testing - 5 hr BW (28 days), Post Doc (6 days)
Packing CTRL and spare - 5 hr BW - 6 days (2 per system, 2 destinations per system)
Test with NRPAOS - 5 hr BW (60 days/1 day per command)
Test with LUAOS - 5 hr BW (30 days/1 day per command)

<table>
<thead>
<tr>
<th>Task</th>
<th>Start Date</th>
<th>End Date</th>
<th>Hours</th>
<th>Labor</th>
<th>Cost</th>
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<tr>
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<td>Direct Labor</td>
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<tr>
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<td>Jul 2015</td>
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<td>Direct Labor</td>
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Total Hours: 1,254

Benefits: $21.67
Rudiments: $12.26
Labor Subtotal: $151.09

Nonabor

For the TMT and its subcomponents to be shipped to the LSIFP and NRPAOS versions for integration, each component of this task will be moved to the TMT Project Create and the AO5 will be shipped at the site. This includes the cost of shipping to the site and the NRPAOS versions were obtained online via the TMT website.

<table>
<thead>
<tr>
<th>Task</th>
<th>Type</th>
<th>Start Date</th>
<th>End Date</th>
<th>Hours</th>
<th>Unit Cost</th>
<th>Subtotal Cost</th>
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<tbody>
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<td>$40.00</td>
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Total Nonabor: $766

Rudiments: $5
Nonabor Subtotal: $806

Total: $151.09

Travel

Four extended domestic trips will be required to integrate the AO5s with the NRPAOS and LSIFP systems at their respective versions, 2 trips each location:

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<th>Destination</th>
<th>Duration</th>
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<th>End Date</th>
<th># of Days</th>
<th>Cost Trip</th>
<th>Travel Cost</th>
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<tbody>
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<td>Extended (40 days)</td>
<td>Dec 2014</td>
<td>Mar 2015</td>
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Total Trips: 4

Total Travel: $137,300

TOTAL: $216

Contingency

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<tr>
<th>Factor</th>
<th>Probability</th>
<th>Impact on Estimate</th>
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</thead>
<tbody>
<tr>
<td>Technical</td>
<td>6%</td>
<td>Integration of the components does not require any major effort.</td>
</tr>
<tr>
<td>Cost</td>
<td>6%</td>
<td>Testing at the NRPAOS and LSIFP vector facility will ensure the readiness of NRPAOS/LSIFP and AO5</td>
</tr>
<tr>
<td>Schedule</td>
<td>4%</td>
<td>Delay in completion impacts the next phase and at the end could impact the AO5 integration</td>
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TOTAL: 22%

Pricing Data Report

TMT BUS CST 06.07A REL.01
Monday, September 11, 2006
TMT Program Confidential Data

Page 23 of 318
Cost Estimate - Risk analysis

- Primitive method - bulk percentage rule of thumb
  - 15% for civil works, 10% at contract signing
  - 30% for technical systems
  - Rates pronounced by grizzled veterans

- Better method - Standard Risk Factor/Percentage
  - One method of this type described here

- Best method – cost of point design response to each risk estimated one by one
  - Not usually practical
(%Contingency used) / (% Project complete)
Contingency Experience of Past DOE Office of Science Projects
## LIGO Advanced LIGO Construction

### LIGO.406.4.1 Pathfinder

<table>
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<tr>
<th>Activity ID</th>
<th>Activity Description</th>
<th>Orig Dur</th>
<th>Start</th>
<th>Finish</th>
<th>Lat Start</th>
<th>Lat Finish</th>
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<th>Budgeted Cost</th>
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Schedule - Integration

- Project Management integrates detailed schedules and reviews all schedule ties between subprojects with those developing detailed schedules.
- Identify all **Critical Paths** (paths through schedule with no extra time (slack)).
- Test alternate approaches to Critical Path.
- Test alternate project strategies.
- Attempt to build schedule slack in critical operations.
- Develop menu of workarounds for anticipated schedule risks.
Figure 8-4. Earned value analysis—behind schedule, overspent.

Earned Value Analysis

Cumulative Spending (Thousands)

Time, Working Weeks

- BCWS
- ACWP
- BCWP

Spending Variance
Schedule Variance
Date of progress measurement
Figure 8-6. Earned value analysis—behind schedule, spending on target.

**Earned Value Analysis**

Cumulative Spending

Time, Working Weeks

- BCWS
- ACWP
- BCWP

Date of progress measurement
Figure 8-5. Earned value analysis—ahead of schedule, spending on target.

Earned Value Analysis

Cumulative Spending

Time, Working Weeks

BCWS  ACWP  BCWP

Date of progress measurement
LIGO Cost Schedule Status

- **Original Plan** - $250M
- **Current Plan** - $292M
- **Cooperative Agreement (Funding)** - $292M
- **Performance** - $285M
- **Actuals Costs** - $284M

$ Millions vs LIGO Quarter
LIGO – a centralized scientific tool

Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)

Livingston Observatory
Louisiana
One interferometer (4km)

Hanford, WA -> Livingston, LA
Project configurations

- Composite operating+project setting - NuMI
- Multiple support sources - TMT
- Collaborative projects – Keck, LSST
- Global projects – ALMA, ITER, ILC, SKA
- Bottom-up collaboratories – NEES, Earthscope, NEON, OOI
- Almost big science – CDMS II, Borexino
Lessons for Big Science Projects

- Manage culture at the individual and group level
- Structure the linear project inside your real project and make sure that you are managing both the linear attributes and the complications adequately
- On day one, start to structure everything progressively as if it is a project
- Big science is different from small science
- [http://www.projectscience.org](http://www.projectscience.org) for case studies