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Technical Evaluation of Alternative Design Concepts for the LIGO-II Seismic Isolation System

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1 INTRODUCTION

The Suspension and Isolation Working Group (SWG) of the LIGO Science Collaboration (LSC) has been pursuing two promising seismic isolation concepts for the LIGO-II mission, denoted the ‘soft’ and the ‘stiff’ systems. The LIGO Laboratory management believe that funding and personnel limits will not permit continued development of the two concepts and that research on the two alternatives is mature enough to support a selection. The SWG chairman and LIGO Laboratory management formed an advisory group, in early January, to provide technical evaluation and guidance on the two alternative design concepts for seismic isolation. The recommendation of this Technical Advisory Group (TAG), which is documented in this report, serves as input to a decision by the LIGO Laboratory on which concept to pursue for LIGO-II. The LIGO Laboratory will consider additional factors[1] such as organizational, staffing and programmatic concerns in making a selection.

2 CHARTER

The charter of the TAG was to review the two concepts, including supporting documentation, simulations, analyses and prototyping work, and provide a technical evaluation of the two designs. Requirements and a set of criteria were established as the basis for the technical evaluation. As part of the evaluation, the TAG requested additional information from the LSC team working on furthering the two concepts, raised questions regarding technical issues and visited the prototype units which are under development.

3 SUMMARY

After careful consideration and much discussion of the information provided to the TAG, it is the unanimous advice of the TAG that if[2] (a) the documented requirements are complete and satisfactory for LIGO-II (especially regarding isolation performance) and that (b) only a single seismic isolation system can be pursued, then the ‘stiff’ concept should be adopted for LIGO-II.[3]

4 RELEVANT DOCUMENTS

D. Shoemaker, D. Coyne, LIGO-II Seismic Isolation Design Requirements Document, LIGO-E990303-02, 11/99.

D. Shoemaker, D. Coyne, Evaluation Criteria for the LIGO-II Seismic Isolation System, LIGO-E990304-01, 8/99.

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[1] A very preliminary costing exercise by the LIGO Lab as part of its preliminary proposal to the NSF indicated that the cost of the two systems was not a significant discriminator; Additional independent costing is in-process by the LIGO Lab.

[2] It should be noted that not all of the TAG members accept these two assumptions.

[3] This should not be construed as endorsement for all aspects of the ‘stiff’ design. Clearly a conceptual design review is required as part of its development process.

The GEO Suspension Team, LIGO-II Suspension: Reference Designs, LIGO-T000012-00, 1/31/00

The principal documents for the ‘stiff’ system:

J. Giaime, B. Lantz, S. Richman, D. DeBra, C. Hardham, J. How, W. Hua, Baseline LIGO-II Implementation Design Description of the Stiff Active Seismic Isolation System, LIGO-T000024-00, 3/8/00

B. Lantz, W. Hua, S. Richman, J. How and the stiff team, Computer Simulation and Modeling of the Stiff Design, LIGO-T000016-00, 2/11/00

B. Lantz, R. Stebbins, C. Hardham, J. Giaime, The Experimental Program in Support of Stiff-Suspension, Active Seismic Isolation for LIGO-II, LIGO-T000015-00, 2/14/00

Additional documentation relevant to the ‘stiff’ approach can be found at http://lsuligo.phys.lsu.edu/active/active.html

The principal documents for the ‘soft’ system:

A. Bertolini, G. Cella, R. DeSalvo, S. Marka, K. Numata, V. Sannibale, A. Takamori, SAS Baseline Design and Prototypes Test Program Plan, LIGO-T0000029-00, 3/6/00

G. Cella, V. Sannibale, A. Takamori, SAS Simulation Plan for LIGO-2, LIGO-T000019-01, 3/00

Additional documentation relevant to the ‘soft’ approach can be found at http://www.ligo.caltech.edu/~citsas/

N.B.: Documented prototype test results are pending for both design concepts.

5 THE TWO APPROACHES

5.1. The ‘Stiff’ Approach

The ‘stiff’ system design evaluated by the TAG is well described by the references cited above. A single baseline design was provided and during the TAG evaluation process the design did no change.

5.2. The ‘Soft’ Approach

The ‘soft’ approach was more difficult to evaluate because many options on the basic approach were proposed as potential adaptations of the ‘soft’ design “toolkit”. The TAG was not provided with a fixed baseline design which they could evaluate straightforwardly. The ‘soft’ design concepts evaluated are as follows:

BSC: The proposed design approach is to use one isolation system (an Inverted Pendulum (IP) and a chain of Geometric Anti-Spring (GAS) filters) per core optic suspension and then another isolation system (with a short GAS filter chain) to independently support an optics table for ancillary optics.[1]

HAM: A progression of designs were proposed and explored: (a) an all under the table, passive isolation approach based on a commercial isolator (Minus-K) with inertial stabilization at the HAM optics table (at the top of the SEI isolation stack), then a few different designs based on an IP and GAS filters culminating in (b) a design which has all elements under the optics table so as not to block or limit access to the chamber apertures or flexibility in positioning of optics. It is this later design concept which has been evaluated.

6 EVALUATION

The following evaluation comments represent majority, but not necessarily unanimous, opinions.

6.1. The 'Stiff' Approach

The 'stiff' system appears to be an elegant and efficient solution for LIGO-II. It is flexible, it fits easily into the vacuum envelope and can be adapted for different configurations. The isolation performance of the system can be improved in the future by the development of improved controllers and transducers. Feed forward and overall multiple input /multiple output control and sense signals can be included easily if these are required.

Given that the suspension design will be carried out by the GEO group in Glasgow, one of the principal advantages of the stiff system is that it facilitates independent development of the seismic and isolation systems. The 'stiff' system, coupled with the multiple-pendulum suspension system, incorporates the isolation benefits of multiple pendulum and springs, for horizontal and vertical isolation respectively. It incorporates these elements of the 'soft' system while maintaining a high impedance mechanical interface which serves to decouple the seismic isolation and suspension subsystems. The result is an easily managed and easily reconfigurable interface.

Other advantages or positive points of the 'Stiff' approach are as follows:

- Compact and common design can be used in all chambers
- The potential for low residual motion (and velocity) offers the potential for simplifying the lock acquisition process by approaching an adiabatic transition through the interferometer fringes. The 'stiff' system is more likely than the 'soft' system to lead to lower rms motion, due to its two, full six degree of freedom active isolation stages.[2]
- Normal modes and parasitic resonances are likely to be less troublesome because of the small

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[1] Alternatively, a single chain could support one optics table per BSC chamber with suspensions and ancillary optics supported on the same table. This stiff, common interface eases the complexity and difficulty of the integration of components on the isolated platform and may help to decouple the suspension controls and the isolation controls (i.e. a more manageable interface). However, this is in conflict with the basic design philosophy of the 'soft' concept.

[2] The need for independent testability of the suspensions and the ability to accommodate assembly tolerances force a high (relative to the residual seismic isolation system motion) dynamic range for suspension actuation. As a consequence it is possible that the suspension actuation design may not benefit from the potential for lower residual motion.

number of independent mechanical components

- Flexibility: The system is flexible and can easily accommodate different suspension designs and reconfiguration of the isolated components, by changes are made in software and not in hardware.
- Upgradeability: The system can be improved directly by improving the transducer noise floor (which is likely to require the development of custom sensors) and implementing higher servo gains (which may not be trivial). The design approach facilitates retrofit of the sensor packages (which requires an incursion into the vacuum system).
- There are no components under high stress.
- The system is tolerant to assembly errors and can be modified in situ by reprogramming.
- Diagnostic transparency: While much has been made of the stiff system's total reliance on sensors, there is in fact also a qualitative and quantitative advantage to this. The very fact that the stiff platform is well instrumented with adequate SNR to register disturbances at *all relevant levels* (anything that can transmit detectable vibration to the mirror) in principle permits complete assurance that the designs (and deployed instantiations) are free from nonlinearities, creak, strain release, and so on, also at *all relevant levels*.

Disadvantages or criticisms are as follows:

- Design Heritage: There is not as much heritage or experience with this system as with the ‘soft’ system. However, neither system has been tried in a high sensitivity interferometer to date.
- Vacuum Compatibility: Requires vacuum compatible transducers and controllers - this is not different for the soft system. However, the approach of the ‘stiff’ concept is to encapsulate commercial sensors and contend with potential thermal management problems.
- Reliability: Compared to the ‘soft’ approach, the ‘stiff’ system may have a higher failure rate because of the increased number of degrees of freedom which are controlled with in-vacuum sensors and actuators.
- Control robustness against resonant features: Mechanical reactance of structural members may be a factor in limiting the gain and/or robustness of the control loops. Measures to damp the structure and/or individualized adjustments to the control matrix (system identification) would mitigate such problems, but these add risk and increase development and implementation costs.
- Isolation Margin & SNR of sensors: Although it meets the isolation requirement, there is not as much margin at 10 Hz with the currently chosen Commercial-off-the-shelf (COTS) sensors, as is possible with the ‘soft’ system. The estimated isolation for the ‘stiff’ system is 10 times better than the requirement at 10 Hz for the BSC version. Both the ‘soft’ and the ‘stiff’ systems have little or no margin on the requirements for the HAM version, though it is likely that the requirements will be relaxed as the LIGO-2 design evolves. If it is deemed worthwhile to increase the margin of suppression of seismic noise, then it is also likely that additional R&D will be needed to obtain some noise margin on the geophones (especially on the inner-stage geophones).
- Cross-coupling of actuators: While the design is relatively insensitive to lack of actuation orthogonality, the modeling has not explored the interdimensional cross-couplings in enough detail to say it's immune. This is subject to better engineering (e.g., flatter “sweet spots” for the voice coils) but might also add engineering costs.

6.2. The ‘Soft’ Approach

While we find no fundamental problems with the ‘soft’ approach, it appears to be a non-optimal solution for LIGO-II. It is a mechanical solution with not much flexibility, once built, to accommodate to different suspensions and optical configurations within the chambers. It also has the same shortcomings of all mechanical solutions, one needs to rebuild to fix a problem. There is little doubt that if significantly more isolation (or a lower frequency of seismic noise crossover to thermal noise) were required, the ‘soft’ design would be superior to the ‘stiff’ design for the BSC version. The HAM version of the ‘soft’ design has little estimated margin in isolation and is not mature enough a concept to be a convincing design.

Other advantages or positive points of the ‘Soft’ approach are as follows:

- Experience in VIRGO and in several test systems.
- The design shows significant margin in the estimated isolation for the BSC version.
- The design is most likely vacuum compatible (the transducers are custom VIRGO derivatives that have been designed to be vacuum compatible).
- The inertial active damping controls operate below the interferometer frequency range of interest; the balance of isolation, including at the micro-seismic peak, is entirely passive. The passive filters also shield the mirror from possible accelerometer and actuator excess noise.
- The low mechanical compliance allows precision positioning of the individual optical components at negligible power consumption levels.
- Independence: The capability of interleaving two or even three independent chains in the same tower allows for independent and full control of the inner test mass and folding mirror in the 2 km interferometer without requiring large actuation dynamic range requirement for static alignment reasons. This also isolates these suspensions from dynamic cross-coupling.
- Dynamic Range: The large dynamic range of the SAS allows the rotation of individual optical elements off axis by as much as 10-20 mrad for tune-up reasons. Large longitudinal positioning range is trivial.

Disadvantages are as follows:

- HAM chamber fit: The system is not compact. As a result it fits in the BSC chamber, but may not fit in the HAM chamber; If it does fit in the HAM chamber, it has little space margin. The implementation of the ‘soft’ system in a HAM chamber is purely a concept, not a design; Not much confidence can be assigned to it. The prior IP and GAS filter designs were impractical by being too large.
- RMS displacement & velocity: Not all experience in VIRGO is good[1] with this system and performance has yet to be quantified by VIRGO. Unfortunately we have no way to be sure if the difficulties are common to the VIRGO design or originate in their differences. The ‘stiff’ system is also likely to result in lower residual motion and velocity, than the ‘soft’ system.
- Interface mechanical impedance: The GEO suspension design and implementation experience is for a mechanically stiff interface (an optics table). The compliant interface point between

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[1] The isolation has been measured at frequencies where it was possible, but limited by sensor noise floor. An unexplained drift of the inverted pendulum, as well as a 10 Hz resonance believed in the body of the inverted pendulum, has been found.

the ‘soft’ seismic isolation system and the suspension system forces the dynamics of the two systems to be much more coupled than in the case of the ‘stiff’ design, i.e. it is a continuous chain of pendulum stages with an arbitrary point in the chain defined as the interface. Although modifications of the basic GEO design are anticipated to adapt to the ‘soft’ design, the magnitude of this design effort and the implications are not known. While this is a feasible approach, it necessitates integrated design of the two systems.

- Material stress and non-Gaussian noise: The high working stress in the GAS springs and their attachment fixtures raises the issue of non-Gaussian noise generation from strain release events. Since there is no clear relation indicating how far below the elastic limit one must stay before strain release events become “negligible” in frequency, we have to concede it is not an obvious problem. However, the mechanical complexity and higher average and peak stresses still argue that whatever the safety margin might be, it is narrower for the soft design.
- Augmentations to the system: The following factors, while not show stoppers are likely to require additions to the baseline design:

  (a) A system to utilize the vertical coil actuator to compensate for temperature induced height changes of the GAS filter chain (range of a few mm)

  (b) There is no separation of horizontal acceleration from tilt. Tilt noise would have to be measured separately and fed forward to the top of the inverted pendulum.

  (c) Angular alignment stability: There is no explicit system or arrangement of restoring forces for vertical torques. It is possible that properly limiting angular (yaw) motion (e.g., by additional constraints or actuators) will compromise isolation.
- Uncontrolled elastic modes: Given the many mechanical elements there is an increased chance of the transmission by the excitation of parasitic normal modes. There is no strategy that can damp these modes from the control locations. It will require ad hoc solutions for most of the normal modes that are discovered.
- Rigid body mode damping: Previous suspension damping research at the University of Glasgow suggests that indirect damping achievable through inter-stage coupling using a limited number of sensors and actuators acting on the top is unlikely to achieve the required damping level without additional actuators and sensors on lower stages, or lossy elements between stages. Sufficient analysis (fully 3D with all cross-coupling terms and active control) of the ‘soft’ design has not been done to demonstrate that the design will not require these additional design complexities.
- Installation & alignment: The process for converging each stage to its appropriate final balance (given that each affects all others) looks laborious and fragile. Dressing wiring and installing and aligning the suspension would need significant jigs and tooling (e.g., fine-control “caging” limiters to freeze stages being worked on). Installing two systems in the same vacuum envelope (or even two suspensions on a common system), wherein the suspended optics are aligned to a fixed external reference angle, position and height, would appear to be extremely difficult.
- Flexibility, extensibility: Moving or re-orienting an optic a few cm (e.g., for RF cavity tuning) would appear to involve a major rebuild for the soft system. Replacing or adding an optic also looks very complicated. These operations are likely given the multiple constraints imposed by the RSE configuration. Likewise, dealing with an unfortunate alignment of a resonant feature with an unforeseen environmental excitation (as is happening now in LIGO I) would involve much more invasive measures for the soft system than for the stiff system.
- Diagnostic transparency: All modes are damped from the top of the IP. The system appears to

rely upon weak or incomplete observability. If problems arise in the system dynamics or control, there is inadequate sensing to fully observe the system and support diagnostics.

- Upgradeability: The seismic isolation performance of the soft design could be improved in the future by replacing the inertial damping system at the top of the inverted pendulum with an active isolation system. Additional passive isolation performance would not be feasible as an upgrade, however, the initial BSC version can be installed with very significant margin beyond the currently defined requirements.
- Wiring harnesses: Cables must be brought down the isolation chain. These cables are likely to be rather stiff in comparison to the GAS filters and pendulum. LIGO-1 experience indicates that the present harnesses exhibit bifurcation points in the stability of their layouts which could present orientation instability problems with the ‘soft’ design. In addition the relatively high stiffness of the wiring may spoil some of the seismic attenuation performance of the ‘soft’ system. (The alternative of developing a wireless power and signal transmission system was not evaluated.)

6.3. Quantitative Evaluation

Nine of the ten TAG members used the criteria defined in the reference cited above to complete an evaluation matrix. The relative importance of each criterion was judged by individual evaluators by assigning a numerical weight to the factor and then scoring each design option against that criterion. Then for each criteria factor, members gave scores for each of the designs. The weighted total evaluation scores are shown in Figure 1. In this figure the curves labeled ‘soft’ and ‘stiff’ represent the score relative to a perfect score of unity. The curve labeled ‘stiff/soft’ is the ratio of the ‘stiff’ score to the ‘soft’ score for each evaluator. The TAG unanimously rates the ‘stiff’ system above the ‘soft’ system when all factors are considered.

There are 28 factors in the evaluation matrix which were numerically scored by the TAG[1]. These factors have been grouped into three categories[2]: functional requirements, performance requirements and risk assessment. The scores in these three categories are shown in Figure 2. Two-thirds of the evaluators rate the ‘stiff’ system above the ‘soft’ system for the categories “risk assessment” and “performance requirements” categories. All evaluators rank the ‘stiff’ system above the ‘soft’ system in the functional requirements” category. Also included in the table below are the average scores for all of the factors which were rated by the evaluators.

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[1] The first 8 factors of the matrix were considered to be ‘prerequisites’; The extent to which these prerequisites were not achieved by either design is reflected in the evaluation of the risk factors. There are also 5 factors which are non-technical (managerial, logistical, cost or staffing) which are reserved for evaluation by the LIGO Laboratory as part of its decision process.

[2] The single factor in the category “flexibility/extensibility” was added to the category “risk assessment”.

Figure 1: Total Weighted Scores

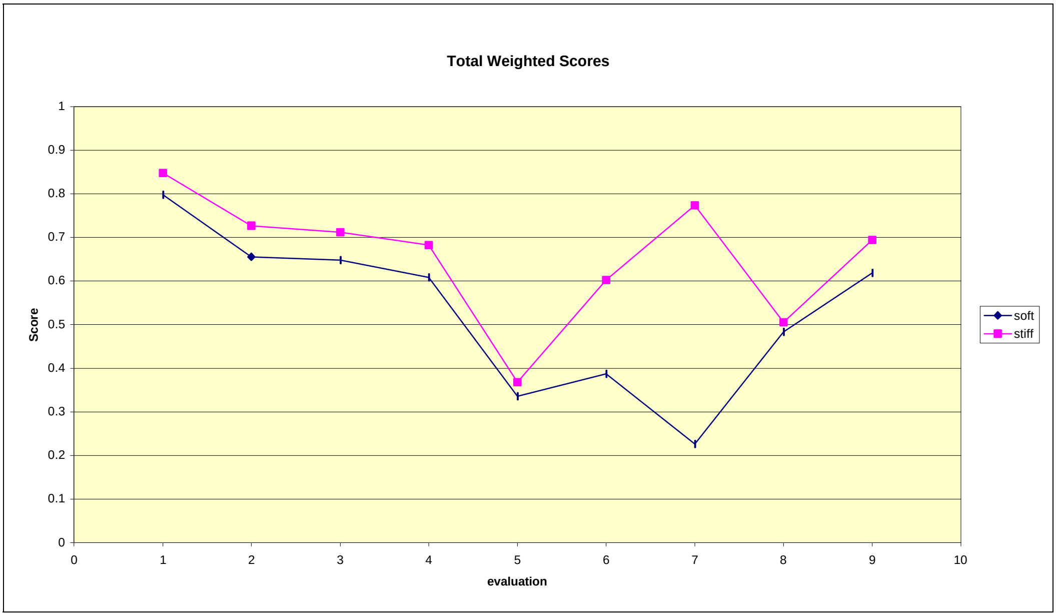
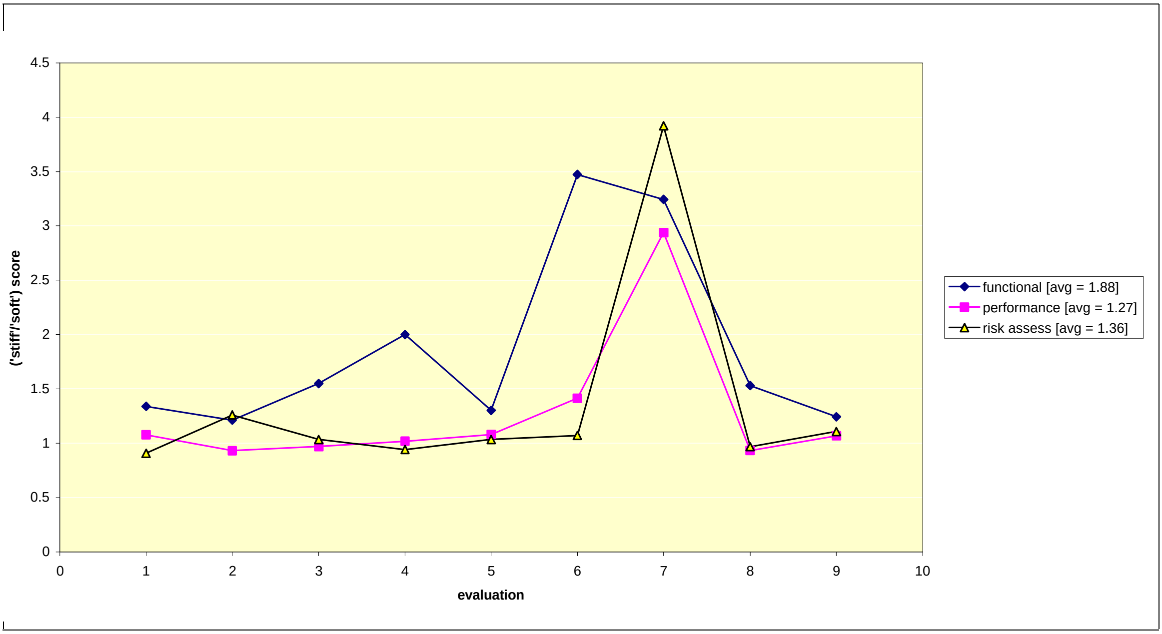


Figure 2: Scores by Category



	Category	Criteria	Average Weighting Factor, W	Average Weighted 'Stiff' Score	Average Weighted 'Soft' Score	Average Weighted 'Stiff'/'Soft' Ratio
1	**Pre-requisites**	Description of design				
2		Definition of SEI/SUS interface details incl. Required SUS modifications (if any)				
3		3D simulation results (incl. SUS model and coupling terms)				
4		control system description				
5		physical layout drawing				
6		development plan				
7		Traceability to previous work				
8		vacuum compatibility				
9	**Functional Requirements**	Fits into LIGO BSC vacuum chamber	9.3	77.3	65.9	1.2
10		Fits into LIGO HAM vacuum chamber	8.7	74.1	26.0	2.9
11		Supports LIGO payloads (weights, positions)	8.0	58.7	42.7	1.4
12		Modular Assembly for rapid installation	5.4	40.8	23.9	1.7
13		Ease of initial alignment, integration	6.9	41.7	21.0	2.0
14	**Performance Requirements**	Meets noise spectrum requirements (X, Y & Z)	10.0	71.7	89.4	0.8
15		Meets total rms noise requirement (X, Y, Z, pitch & yaw)	10.0	72.8	66.1	1.1
16		Meets longitudinal velocity requirement	5.6	30.6	21.9	1.4
17		Meets Actuation requirements for alignment, earth tide and thermal compensation	9.8	75.0	63.0	1.2
18		Meets actuation requirements for microseismic peak suppression	8.7	62.6	60.7	1.0
19		All internal Modes are damped adequately	7.4	38.5	17.0	2.3
20		Drift and Thermal Expansion are within Acceptable Limits	6.8	43.7	27.1	1.6
21	**Risk Assessment**	Validation & completeness of 3D simulation	6.2	41.5	26.3	1.6
22		Pedigree or traceability to previous working SUS design	4.1	16.2	10.3	1.6
23		Pedigree or traceability to previous working SEI design	4.7	15.3	25.7	0.6
24		Successful prototype tests of parts or whole	8.0	42.7	49.8	0.9
25		simplicity/commonality (mechanical & electronic)	4.1	19.6	17.4	1.1
26		development(s) required (maturity of design)	5.1	24.1	21.9	1.1
27		development(s) required (maturity of components)	5.2	22.3	25.8	0.9
28		Testability	4.2	19.2	13.6	1.4
29		facilitates independent development & test of the suspension	4.4	21.7	10.9	2.0
30		Diagnosticability	5.0	31.1	15.6	2.0
31		Robustness of the Development Team				
32		Ease of Installation	4.1	21.0	11.9	1.8
33		Risk of Non-Gaussian Noise	5.6	26.2	24.4	1.1
34		Robustness of Design	6.6	32.8	31.3	1.0
35		Reliability, MTBF, MTTR	7.4	36.4	42.2	0.9
36		Risk of failure to function or perform? (i.e. Will I work?)	8.8	58.5	56.6	1.0
37	**Cost & Schedule**	research & development cost				
38		production cost				
39		assembly & installation tooling costs				
40		schedule				
41	**Flexibility/Extensibility**	Flexibility/Extensibility	4.4	19.8	15.3	1.3
		TOTAL		1135.9	923.4	1.4