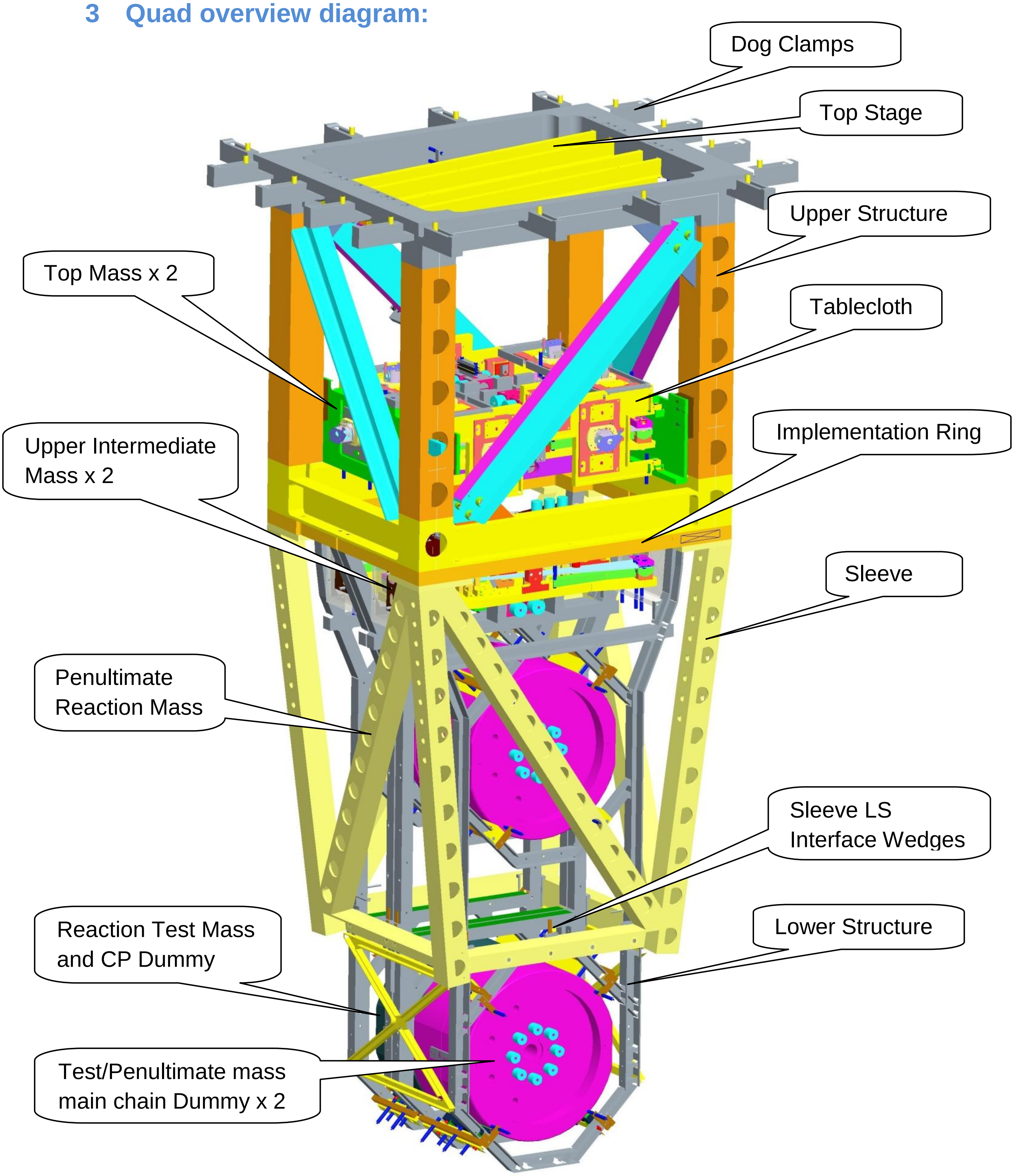
T1000286 – v9 Quad Final Design Document

1 Table of Contents

2 Nomenclature:

PDR-3	-	Product Design Review for RAL mechanical Quad suspension
PRR	-	Production Readiness Review
RAL	-	Rutherford Appleton Laboratories
Quad	-	Quadruple Suspension System
TS	-	Top Stage
TM	-	Top Mass
UIM	-	Upper Intermediate Mass
PEN RE	-	Penultimate Reaction
OSEM	-	Optical Shadow sensor and Electro-Magnetic actuator
MOI	-	Moments Of Inertia
C of G	-	Centre Of Gravity
D distance	-	Effective attachment position of a wire from mass C of G
FEA	-	Finite Element Analysis
BOM	-	Bill of materials
OJEU	-	Official Journal of the European Union (European Tender process)
EQ	-	Earthquake
GA	-	General Assembly
Picture book	-	Pictorial Assembly Sequence
PDS	-	Product Design Specification
VMS	-	Violin Mode Sensor
BO	-	Break Off
M	-	Main (Chain)
R	-	Reaction (Chain)

3 Quad overview diagram:



4 Introduction:

This document aims to bring together all the relevant information and documentation for the ALGO Quad, including a list of the "as-built" parameters, design justifications, record of modifications, references to assembly and specification documentation, requested documentation, and any other relevant supporting documentation. It is the intention that through the links that this document provides, the quad could be manufactured and built from scratch.

5 Summary of design history and development:

The design of the Quad has progressed through several iterations, including early design and development, prototype work, reviews, design iterations, and additions to scope incorporated late on in the design.

5.1 Technology Demonstrator

This was built in Glasgow and documented in G050168-00-Z and P050030-00-R

5.2 Controls Prototype

The first of the Prototypes was the "controls prototype". The intention was this would highlight the more major issues relating to the design philosophy and implementation. This was the first full-size Quad, and it highlighted design issues across the board. There was a major design iteration after this prototype.

5.3 PDR-3

Following the "controls prototype" the design development lead to the Product Design Review - Mechanical (PDR3), which would need to be passed before progressing to the next prototype phase.

The design of the Quad at the stage of this review was comprehensively documented, and is all contained on the PDR3 website. This website has been captured as a documentation list in T1000391-v1.

5.4 PDR-3 Response

Several response documents and document updates came about as a direct result of this review, and these are referenced in T1000392-v1, which is a capture of the RAL PDR3 response page.

5.5 Noise Prototype

On successful implementation of design refinements as a result of feedback from PDR-3, go-ahead was received for the final pre-production prototype – the Quad "Noise Prototype".

The goal of this prototype was to try out the Monolithic suspension, and to highlight more minor mechanical issues that may have been missed during the controls prototype, and to test any new design work that was done as a result of it. It was also to be the last prototype before the final Quad production (16 units) and was therefore the last opportunity to ready the design for production.

5.6 Production Readiness Review

The Quad "noise Prototype" was built at LASTI in 2007, and this was followed by the Production Readiness Review (PRR). The production readiness review was split by RAL into two sections; "Structures" and "Suspension". The RAL web page with links to the "PRR Suspension" documentation is captured in T1000404-v1. The web page with links to the "PRR Structures" documentation is captured in T1000410-v1. These review pages are a record of changes made to the production quad design as a result of the previous reviews, and the Quad "Noise Prototype". They also reference the proposed manufacturing specifications for the RAL OJEU.

5.7 First article

We had planned to build a first article, using production parts, once all of the design details of the quad had been frozen. However, it became apparent that a true first article would involve a considerable delay because the production parts were to be produced serially and so it would not be until near the end of the production process that all of the parts for such a suspension would be ready. Were we to insist that the manufacturers reschedule so as to produce a single set of parts first, the set would not be representative of the final run because all the machines would need to be reset between the first items and the full production run. Because of the setup costs, it would also be very expensive. The thread inserts also presented a serious problem. A quad cannot be assembled without fitting thread inserts, and the parts cannot be cleaned once the inserts are fitted. That meant that all the parts would need to class A clean and assembled in a clean area, further delaying the first article and raising the cost. There was time pressure to have something ready for training sessions for the US staff who were preparing to make the final assemblies. For all these reasons, we elected to produce a "training prototype", based on the duplicate noise prototype at RAL but incorporating all the significant changes that had been made since the noise prototype design. Had we stuck to the original first article concept we would doubtless have avoided some, but not all, of the assembly problems that we experienced during assembly at the sites. We cannot tell what the effect on overall schedule and cost would have been.

5.8 Production and late changes

Since go-ahead was given for quad production, several further changes were made to the quad, mostly based on US requests, but also based on lessons learned from the first article build. All changes to the Quad production hardware, and tooling since PDR-3, are listed in T1000336-v1. This includes several pieces of new hardware that were designed on request from various SUS members.

The net result of all the changes made to the quad since PDR 3, is that there are several small changes to the parameter set. The final "as built" parameter set is recorded in section 6 of this document.

6 As Built Parameters:

See T1000428.

7 Assembly data:

Assembly data can be found throughout the Quad assembly documentation, both in the General assembly procedures (9.2) and the specific assembly procedures (9.3). Document T0900372 "Assembly Data for the Quad Noise Prototype" contains information on clamp wire clamp assemblies, and Blade tip heights. This information is also contained in the wire picture books, and the E1000006 assembly procedure. Blade data can be found in T1000068.

8 Tooling Required:

8.1 Tooling supplied by RAL:

8.1.1 Metal build

D060516	-	Quad Wire Jig
D060370	-	Quad Top Stage blade straightening tooling
D060302	-	Quad LSAT (Lower Structure Assembly Tooling) Main Chain
D060305	-	Quad LSAT Reaction Chain

8.1.2 Glass build

D080321	-	Quad Triple hang tooling
D1000020	-	Quad LS (lower structure) split/rotate tooling
D0902757	-	Silica insertion tooling
D0901564	-	Quad LS – LSAT brace bar
D080246	-	Flourel trimming tool
D1000534	-	Suction plate

8.2 Other tooling:

8.2.1 Metal build:

- Set of Imperial Hexagon socket wrenches (standard)
- Set of imperial Hexagon socket wrenches (ball ended)
- Set of imperial spanners/sockets
- Torque wrench with hexagon socket attachments (3/16 and 5/16)
- Imperial helicoil insert tools (8-32, 1/4-20, 3/8-16 and 1-8 UNC)
- Set of metric block gauges
- Set of digital metric weighing scales
- Pair of wire cutters
- Pair of pliers
- FFT oscilloscope
- Guitar pickup
- Set of weights (slotted weights and hanger or similar) ~ 50kg
- Genie lift or similar
- Solid stack/suspension gazebo or similar

8.2.2 Glass Build:

- See T1000337 for Glasgow glass assembly procedure and tooling.

9 Relevant documents:

9.1 Overview Documents:

M030162-vD - Scope of ALUK Work Packages

D0901346_DATA - Quad ETM/ITM GA Drawing

T1000667-v4 - Revised Quad suspension design for thin Compensator Plate (TCP)

T1000423-v1 - Quad Drawing Tree and Drawing List

T0900590-v7 - Quad BOM and Manufacturing Status

T1000107-v1 - Complete list of Quad Production and Tooling Parts

T010007–v2	-	Cavity optic design requirements document
T1000286-v1	-	Changes to the Quad post PDR-3
T060099-01-K	-	Technical Noise Sources
T060141-02-K	-	Quad Mass Budget
T060115-01-K	-	BSC suspension thermal budget
T060116-00-K	-	BSC suspension failure effects and modes
E050317-02-K	-	Compliance matrix
D050266-00-K	-	Quad ETM/ITM envelope
T010103-05-K	-	Conceptual Design Document (v1 in new DCC)

Important note: The following documents should be used with reference to T1000286, which describes changes to the Quad since these documents were written. The information in document T1000286 outdates these documents, but all the information in them is still relevant unless stated otherwise (in T1000286).

T060142-00-K	-	Quad Overview Document (For review – PDR3)
T050103-00-K	-	Quad Adjustment Scheme
T060132-00-K	-	Quad Tooling Overview

9.2 General Assembly:

E1000006-v6	-	Quad Assembly Procedure
T080165-v1	-	Balancing and Alignment
T1000049	-	Procedure for monolithic re-hang at LASTI
T1000407v1	-	RAL Quad balancing and Alignment procedure

Note – This is the original Quad alignment procedure written by RAL. This document is superseded is by the T080165 alignment document written from experience at LASTI. The T080165 document is more detailed, and should be used in preference to this one. However, this document is useful for reference, and can be referred to as a baseline procedure if required.

E1000030 - Quad Suspension Metal Assembly Hazard Analysis

T060131-00-K - Risk Assessment/Hazard Analysis

T0900372-v1 - Assembly Data for the Quad Noise Prototype ***(This document is still applicable to the Quad, but as theoretical reference data only. Use the information contained in the E1000006 document and in the various specific assembly documents in section 9.3 of this document, for assembly data)***

9.3 Specific:

9.3.1 Top Stage

D060324 - Top Stage GA Drawing

T050233-00-K - Top Stage PDS (including tooling) *(refer to T1000336-v1, section 4.2)*

D060370 - Top Stage Tooling Drawing

D060370_asm_procedure - Top Stage Picture Book

9.3.2 Top Mass

D060403 - Top mass GA Drawing

T050188-00-K - Top Mass PDS *(refer to T1000336-v1, section 4.3)*

D060403_asm_procedure - Top Stage Picture Book

9.3.3 Tablecloth

D060310 - Tablecloth GA Drawing

T050190-00-K - Tablecloth PDS *(refer to T1000336-v1, section 4.4)*

See also section 9.3.16 of this document.

9.3.4 UI Mass

D060375 - UI mass GA Drawing

T060149-00-K - UI mass PDS *(refer to T1000336-v1, section 4.5)*

D060375_asm_procedure - UI Mass Picture Book

9.3.5 Penultimate Reaction Mass ETM/ITM

D060341 - Penultimate Reaction Mass GA Drawing (pg1 ETM, pg2 ITM)

T050227-00-K - Penultimate reaction mass PDS *(refer to T1000336-v1, section 4.6)*

D060341_asm_procedure - Penultimate Reaction Mass picture Book

T1000667-v4 - Revised Quad suspension design for thin Compensator Plate (TCP)

9.3.6 Test Mass (metal dummy)

D060355 - Main Chain Dummy Mass GA Drawing

T050244-00-K - Dummy Optics PDS *(refer to T1000336-v1, section 4.7)*

9.3.7 ETM/ITM Reaction Test Mass (Metal Dummy Compensator Plate and End Reaction Mass)

D060356 - ETM Reaction Chain Dummy Mass GA Drawing

T050244-00-K - Dummy Optics PDS *(refer to T1000336-v1, section 4.8)*

D1002204 - ITM reaction chain Dummy Mass GA drawing

T1000667-v4 - Revised Quad suspension design for thin Compensator Plate (TCP)

9.3.8 Upper structure

D060492 - Upper Structure GA Drawing

T060117-00-K - Upper Structure PDS *(refer to T1000336-v1, section 4.9)*

T050077-00-K - Chain Separation Document

9.3.9 Lower Structure

D060545 - Lower Structure GA Drawing

T060118-00-K - Lower Structure PDS *(refer to T1000336-v1, section 4.10)*

T1000348-v1 - UIM EQ stop re-design

9.3.10 Sleeve

D070552 - Sleeve Drawing

T060148-00-K - Sleeve PDS *(refer to T1000336-v1, section 4.11)*

9.3.11 Sleeve – LS Interface

T1000369-v1 - Spacer Wedges PDS and Assembly Information

T0900591-v1 - Hardware for test at Monolithic

T1000208-v1 - LASTI test on Quad tooling and Hardware

D10001505 - Spacer Wedge Type A GA Drawing

D10001506 - Spacer Wedge Type B GA Drawing

D10001507 - Spacer Wedge Type C GA Drawing

D10001508 - Spacer Wedge Type D GA Drawing

9.3.12 Structural Development and Resonance Testing

T060135-00-K - Structural Design Development

T060088-00-K - FEA of SUS ETM Structure using ANSYS Workbench

T060087-00-K - FEA of SUS ETM Structure using ANSYS Classic

T060059-01-K - FEA of SUS ETM Structures – March 2006

T060086-00-K - FEA of Bench Test Structure

T1000410-v1 - Quad Structure PRR web page capture

9.3.13 EQ and bump stops

T060053-00-K - Earthquake Stop Analysis

T060098-01-K - Mechanical Calculations on EQ stops – Part 2

T060176-02-K - Earthquake Stop Analysis - Part 3

T060139-00-K - Earthquake Stop Overview

T060144-00-K - Earthquake Stops in Lower Structure *(refer to T1000336-v1, sections 4.10, 6.4 and 6.5)*

T1000377-v1 - Description of the D0902757 – Silica Insertion Tool, and Assembly Manual

T060100-00-K - Earthquake and shock loads

D060544 - Silica tipped EQ stop assembly drawing

D060546 - 10mm Flourel part drawing

D080240 - Assembly drawing for PenRe mass bump stop

D080245 - 8mm Flourel part drawing

D080241 - CP bump stop (ETM version)

D1003106 - Thin CP bump stop (ITM version)

9.3.14 Wire and Wire clamps

D0902643 - Top Wire “Clamp Wire Clamp” GA Drawing

D0902644 - Middle Wire “Clamp Wire Clamp” GA Drawing

D0902645 - Bottom and Final “Clamp Wire Clamp” GA Drawing

D060516 - Wire jig GA drawing, and “Clamp Wire Clamp” Assembly Instructions and Data

T060042-00-K - Wires and Clamps PDS *(refer to T1000336-v1, sections 4.5.9, 6.6.2, 4.7.1 and 6.1)*

T050194-00-K - Wire Clamp Test Procedure

9.3.15 Blades

T060047-00-K - Blades PDS

D060235 - Top Blade Drawing

D060236 - Middle Blade Drawing

D060237 - Bottom Blade Drawing

C1001163 - OJEU Spec for Blade Production

T1000068-v1 - Quad Blade Characterisation Data, and Blade-Blade Clamp Pairing

T0900344-v3 - Characterisation of Final Quad Blades

T1000149-v1 - Double Check on Final Quad Blades

T080028-v1 - Lateral Blade Movement in Clamps Experiment

T080030-v1 - Tilt Test on RAL Noise Prototype

T080059-v1 - Tilt Tests on the RAL Noise Prototype – Part 2

9.3.16 Magnets, OSEMs and ECDs

T060122-00-K - OSEM and ECD magnet attachment PDS

T050093-00-K - ECD Requirements for Quad Suspensions

T050105-00-K - Quad Magnets at Top Mass

T050271-00 - Magnet Strength Considerations

T060001-00-K - Increase strength in PM/UIM actuators

T060017-00-K - Investigation into Vac-seal flag attachment

T080245-v1 - Report on Bonding Viton Stops, Magnet Holders and break-off Prisms on the NP-Type at LASTI

9.3.17 OSEM and ESD Cable Routing (Mechanical)

T1000211-v1 - Cable Clamp – Flourel Insert Design Proposal

T1000010-v1 - Proposal for RAL provision for Quad cable routing

T0900380-v1 - Quad Noise Prototype Cable routing

9.4 Other relevant Reference Documentation:

9.4.1 Design

T1000405-v1 - "As Designed" Parameter Set

Note – this shows the theoretical parameters that have been designed into the Quad.

9.4.2 Manufacture

T1000406-v1 - Technical Risks Taken by RAL in Placing the OJEU Contract

T1000428-v1 - Quad "As Built" Parameter Set

Note – This document shows how the theoretical parameters have been implemented in practice. It lists the physical break-off points, mass moments of inertia, and wire lengths for the built Quads.

C1001163-v3 - OJEU Quad Machining Spec

C1001164-v1 - OJEU Spec for Quad Blade Production

C1001172-v1 - OJEU Quad Welding Spec

9.4.3 Testing of Late Additions to Production Hardware and Tooling

T1000208-v1 - LASTI Tests on Quad Production Hardware and Tooling

T0900591-v1 - Proposal for RAL Hardware Testing at the Monolithic

9.4.4 CAD File Conversion Pro-E – Solidworks

T1000304-v1 - Quad and BS Model Properties for CAD Conversions

E0900483-v4	-	Statement of Work for Pro-E File Translation
D1001440-v2	-	Quad Pro-E Files from RAL – June 2010

10 References to specifically requested information:

10.1 Layout of OSEMs and Orientation of Magnet Polarities

- For layout of OSEMs, reference D0901346_DATA page 5
- For General philosophy on magnet orientation, see T060122-00-K
- For ECD magnet layout specifications see T050093-00-K
- For considerations for magnetic interactions at the top mass, see T050105-00-K
- For layout of magnets polarities at the top mass, see D060403_asm_procedure

10.2 The Flag Lever Arms at the Top, UI and Penultimate Mass

- For flag lever arms at each stage, see D0901346_DATA page 4

10.3 Height of each mass C of G, relative to the optics table

- For a pictorial version of this dimensional information, reference D0901346_DATA page 2
- For a tabulated version of this dimensional information, reference T1000428-v1, or section 6 of this document.

10.4 Reference Measurement Data for Rough Alignment

- Reference D0901346_DATA page 3

11 Appendix A – Mass properties for Metal masses.

11.1 Main Top mass

VOLUME = 3.2092303e+06 MM^3

SURFACE AREA = 1.0351966e+06 MM^2

AVERAGE DENSITY = 6.8393970e-06 KILOGRAM / MM^3

MASS = 2.1949200e+01 KILOGRAM

CENTER OF GRAVITY with respect to LIGO_CSYS coordinate frame:

X Y Z -8.1037110e-02 2.3463773e-01 -6.4449500e-02 MM

INERTIA at CENTER OF GRAVITY with respect to LIGO_CSYS coordinate frame: (KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 4.6003463e+05 -3.7559948e+04 1.7184099e+03

Iyx Iyy Iyz -3.7559948e+04 7.2723418e+04 4.6546253e+01

Izx Izy Izz 1.7184099e+03 4.6546253e+01 4.7217665e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 6.9114514e+04 4.6331497e+05 4.7250522e+05

ROTATION MATRIX from LIGO_CSYS orientation to PRINCIPAL AXES:

0.09564	-0.97746	0.18823
0.99542	0.09402	-0.01757
-0.00052	0.18905	0.98197

ROTATION ANGLES from LIGO_CSYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 1.025 10.850 84.411

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 5.6114524e+01 1.4528769e+02 1.4672157e+02 MM

11.2 Reaction Top Mass

VOLUME = 3.2681305e+06 MM^3

SURFACE AREA = 1.0981905e+06 MM^2

AVERAGE DENSITY = 6.7751809e-06 KILOGRAM / MM^3

MASS = 2.2142175e+01 KILOGRAM

CENTER OF GRAVITY with respect to LIGO_CSYS coordinate frame:

X Y Z -2.9900294e-01 2.3259280e-01 -7.2603077e-02 MM

INERTIA at CENTER OF GRAVITY with respect to LIGO_CSYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 4.6117648e+05 -3.7561070e+04 1.7139341e+03

Iyx Iyy Iyz -3.7561070e+04 7.4251818e+04 -4.3598626e+01

Izx Izy Izz 1.7139341e+03 -4.3598626e+01 4.7263418e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 7.0639235e+04 4.6443241e+05 4.7299083e+05

ROTATION MATRIX from LIGO_CSYS orientation to PRINCIPAL AXES:

0.09574	-0.97444	0.20322
0.99541	0.09378	-0.01925
-0.00030	0.20413	0.97894

ROTATION ANGLES from LIGO_CSYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 1.127 11.725 84.389

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 5.6482362e+01 1.4482753e+02 1.4615586e+02 MM

11.3 Main UI mass

VOLUME = 3.0148772e+06 MM^3

SURFACE AREA = 8.3683853e+05 MM^2

AVERAGE DENSITY = 7.4093423e-06 KILOGRAM / MM^3

MASS = 2.2338257e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X   Y   Z   8.5633228e-03 0.0000000e+00 -2.7165591e-02 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 5.0875622e+05 -1.3211675e+04 0.0000000e+00

Iyx Iyy Iyz -1.3211675e+04 7.1054293e+04 0.0000000e+00

Izx Izy Izz 0.0000000e+00 0.0000000e+00 5.1808050e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3   7.0655872e+04 5.0915464e+05 5.1808050e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

0.03014	-0.99955	-0.00001
0.99955	0.03014	0.00000
0.00000	-0.00001	1.00000

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z   0.000   0.000   88.273

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 5.6240541e+01 1.5097332e+02 1.5229091e+02 MM

11.4 Reaction UI Mass

VOLUME = 3.2046529e+06 MM^3

SURFACE AREA = 9.9489250e+05 MM^2

AVERAGE DENSITY = 7.0432302e-06 KILOGRAM / MM^3

MASS = 2.2571108e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z 2.8597774e-01 -7.1392107e-02 -8.8111271e-02 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 5.1046190e+05 -1.3210302e+04 -5.0610946e+01

Iyx Iyy Iyz -1.3210302e+04 7.3027023e+04 5.2079013e+01

Izx Izy Izz -5.0610946e+01 5.2079013e+01 5.1894225e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 7.2628436e+04 5.1086015e+05 5.1894259e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

0.03016	-0.99952	-0.00645
0.99955	0.03016	0.00031
-0.00011	-0.00645	0.99998

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 0.000 -0.369 88.272

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 5.6725314e+01 1.5044390e+02 1.5162933e+02 MM

11.5 Main UI mass after addition of pitch adjuster

VOLUME = 3.0389794e+06 MM^3

SURFACE AREA = 8.3637899e+05 MM^2

AVERAGE DENSITY = 7.3593953e-06 KILOGRAM / MM^3

MASS = 2.2365051e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z -1.7056362e-03 1.2937659e-02 -5.4003373e-03 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 5.0470962e+05 -1.3206404e+04 8.0840059e+00

Iyx Iyy Iyz -1.3206404e+04 7.2402399e+04 -1.3741691e+01

Izx Izy Izz 8.0840059e+00 -1.3741691e+01 5.1821582e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 7.1999337e+04 5.0511267e+05 5.1821582e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

0.03051	-0.99953	0.00065
0.99953	0.03051	-0.00005
0.00003	0.00065	1.00000

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 0.000 0.000 88.252

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 5.6738690e+01 1.5028277e+02 1.5221953e+02 MM

11.6 Reaction UI mass after addition of pitch adjuster

VOLUME = 3.1917239e+06 MM^3

SURFACE AREA = 9.6697256e+05 MM^2

AVERAGE DENSITY = 7.0361467e-06 KILOGRAM / MM^3

MASS = 2.2457437e+01 KILOGRAM

CENTER OF GRAVITY with respect to LIGO coordinate frame:

X Y Z 3.1101980e-02 -2.1234593e-02 -1.8802943e-03 MM

INERTIA at CENTER OF GRAVITY with respect to LIGO coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 5.1817090e+05 -5.0102707e+01 3.4120911e+01

Iyx Iyy Iyz -5.0102707e+01 7.3433036e+04 -1.3211797e+04

Izx Izy Izz 3.4120911e+01 -1.3211797e+04 5.0521954e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 7.3029154e+04 5.0562332e+05 5.1817101e+05

ROTATION MATRIX from LIGO orientation to PRINCIPAL AXES:

0.00011	-0.00284	1.00000
0.99953	-0.03055	-0.00020
0.03056	0.99953	0.00284

ROTATION ANGLES from LIGO orientation to PRINCIPAL AXES (degrees):

angles about x y z 3.972 89.837 87.779

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 5.7025360e+01 1.5004912e+02 1.5189954e+02 MM

11.7 Penultimate Reaction Mass (ETM)

VOLUME = 6.8487755e+06 MM^3

SURFACE AREA = 1.3481959e+06 MM^2

AVERAGE DENSITY = 7.7905983e-06 KILOGRAM / MM^3

MASS = 5.3356058e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z 1.0589363e-01 4.5216104e-02 -4.8087362e-03 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 8.5258658e+05 -5.8684678e+01 4.4072984e+01

Iyx Iyy Iyz -5.8684678e+01 4.9840055e+05 2.3754754e+01

Izx Izy Izz 4.4072984e+01 2.3754754e+01 4.8630925e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 4.8630920e+05 4.9840059e+05 8.5258659e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

-0.00012	0.00017	-1.00000
-0.00197	1.00000	0.00017
1.00000	0.00197	-0.00012

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 0.000 -89.988 -0.113

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 9.5469439e+01 9.6649009e+01 1.2640882e+02 MM

11.8 Penultimate Reaction Mass (ITM)

VOLUME = 7.5704306e+06 MM^3

SURFACE AREA = 1.3566720e+06 MM^2

AVERAGE DENSITY = 7.8010270e-06 KILOGRAM / MM^3

MASS = 5.9057134e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z 9.5670611e-02 4.0851604e-02 -4.3450374e-03 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 9.2327494e+05 -5.8708519e+01 4.4074302e+01

Iyx Iyy Iyz -5.8708519e+01 5.3557103e+05 2.3761318e+01

Izx Izy Izz 4.4074302e+01 2.3761318e+01 5.2347974e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 5.2347969e+05 5.3557107e+05 9.2327496e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

-0.00011	0.00015	-1.00000
-0.00197	1.00000	0.00015
1.00000	0.00197	-0.00011

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 0.000 -89.989 -0.113

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 9.4148571e+01 9.5229690e+01 1.2503435e+02 MM

11.9 Penultimate main mass (metal dummy)

VOLUME = 1.4412945e+07 MM^3

SURFACE AREA = 7.9339428e+05 MM^2

AVERAGE DENSITY = 2.7317465e-06 KILOGRAM / MM^3

MASS = 3.9372513e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z 2.1990974e-02 0.0000000e+00 -7.6279505e-03 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 6.0883801e+05 5.0764239e+02 0.0000000e+00

Iyx Iyy Iyz 5.0764239e+02 4.0480211e+05 0.0000000e+00

Izx Izy Izz 0.0000000e+00 0.0000000e+00 3.9763469e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 3.9763469e+05 4.0480085e+05 6.0883927e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

0.00000	-0.00249	-1.00000
0.00000	1.00000	-0.00249
1.00000	0.00000	0.00000

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 89.999 -89.857 89.999

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 1.0049526e+02 1.0139678e+02 1.2435257e+02 MM

11.10 Test mass (Metal Dummy)

VOLUME = 1.4358529e+07 MM^3

SURFACE AREA = 7.6737970e+05 MM^2

AVERAGE DENSITY = 2.7398109e-06 KILOGRAM / MM^3

MASS = 3.9339653e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z 0.0000000e+00 0.0000000e+00 7.3410470e-03 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 6.0745643e+05 5.0763481e+02 0.0000000e+00

Iyx Iyy Iyz 5.0763481e+02 4.0437160e+05 0.0000000e+00

Izx Izy Izz 0.0000000e+00 0.0000000e+00 3.9651212e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 3.9651212e+05 4.0437033e+05 6.0745769e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

0.00000	-0.00250	-1.00000
0.00000	1.00000	-0.00250
1.00000	0.00000	0.00000

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 90.000 -89.857 90.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 1.0039521e+02 1.0138516e+02 1.2426326e+02 MM

11.11 ETM Compensator Plate (metal dummy)

VOLUME = 9.4944321e+06 MM^3

SURFACE AREA = 6.4204424e+05 MM^2

AVERAGE DENSITY = 2.7714181e-06 KILOGRAM / MM^3

MASS = 2.6313041e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z 0.0000000e+00 0.0000000e+00 -1.0971890e-02 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 4.1570992e+05 1.3473926e+02 0.0000000e+00

Iyx Iyy Iyz 1.3473926e+02 2.3913106e+05 0.0000000e+00

Izx Izy Izz 0.0000000e+00 0.0000000e+00 2.3599600e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 2.3599600e+05 2.3913095e+05 4.1571003e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

0.00000	-0.00076	-1.00000
0.00000	1.00000	-0.00076
1.00000	0.00000	0.00000

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 0.000 -89.956 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 9.4703666e+01 9.5330610e+01 1.2569260e+02 MM

11.12 ITM Compensator Plate (Thin – metal dummy)

VOLUME = 7.1550019e+06 MM^3

SURFACE AREA = 5.9667642e+05 MM^2

AVERAGE DENSITY = 2.7973238e-06 KILOGRAM / MM^3

MASS = 2.0014858e+01 KILOGRAM

CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:

X Y Z 0.0000000e+00 0.0000000e+00 -1.4419612e-02 MM

INERTIA at CENTER OF GRAVITY with respect to ALIGO_SYS coordinate frame:
(KILOGRAM * MM^2)

INERTIA TENSOR:

Ixx Ixy Ixz 3.2366725e+05 5.5578910e+01 0.0000000e+00

Iyx Iyy Iyz 5.5578910e+01 1.7642557e+05 0.0000000e+00

Izx Izy Izz 0.0000000e+00 0.0000000e+00 1.7516931e+05

PRINCIPAL MOMENTS OF INERTIA: (KILOGRAM * MM^2)

I1 I2 I3 1.7516931e+05 1.7642555e+05 3.2366727e+05

ROTATION MATRIX from ALIGO_SYS orientation to PRINCIPAL AXES:

0.00000	-0.00038	-1.00000
0.00000	1.00000	-0.00038
1.00000	0.00000	0.00000

ROTATION ANGLES from ALIGO_SYS orientation to PRINCIPAL AXES (degrees):

angles about x y z 0.000 -89.978 0.000

RADII OF GYRATION with respect to PRINCIPAL AXES:

R1 R2 R3 9.3551932e+01 9.3886788e+01 1.2716662e+02 MM