INTERNSHIP PROJECT

AT

Liquid Propulsion Systems Center (Valiamala)
Indian Space Research Organisation

COUPLING NUT JOINTS

SAFETY AND SIZING TOOL

Submitted by :

Kashvi Agrawal
Mechanical Engineering Department
IIT Guwahati

Internship Period : 01/12/25 - 01/01/26
Mentor: Mr. Praveen SR (Scientist/Engineer, CSPEG)

PREPARED BY	**Kashvi Agrawal** **Intern - EID**	
REVIEWED BY	**Praveen S R** **DDH, EID-SC&LME**	
APPROVED BY	**Abhilash Narayan** **DH, EID/CSPEG**	

ENGINE INTEGRATION DIVISION

LIQUID PROPULSION SYSTEMS CENTRE, VALIAMALA
THIRUVANANTHAPURAM – 695 547

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PROBLEM STATEMENT

1. Abstract

This report presents the development and validation of a MATLAB-based safety assessment and geometry optimization tool for coupling nut joints. Coupling nut joints are fundamentally different from simple bolted joints in the sense that they are internally threaded and give passage for the flow of fluid through it. These joints are used in pressure-fed propellant feed lines in cryogenic and semi cryogenic engines.

The developed tool takes into consideration multi-material interfaces, geometric constraints and thermal effects (based on user demand) to compute factor of safety (FoS) across six distinct failure modes. A brute-force optimization strategy was employed to identify minimum required geometry modifications to achieve user-defined safety targets. The tool is implemented in dual form: a script-only workflow for batch analysis and an interactive App Designer graphical user interface for parametric studies, enabling accessibility to engineers and technicians. As there is no standard available for these joints, detailed committee guidelines have been taken for design consideration.

2. Introduction

Background and Relevance of Coupling-Nut Joints

Coupling-nut joints are specialized fasteners essential to the integration of pressurized cryogenic fluid systems in launch vehicles and propulsion test facilities. Unlike conventional threaded fasteners, coupling nuts are internally threaded and permit fluid passage through their central bore. The SE2000 Integrated Engine system operated by LPSC encompasses 215 coupling-nut joints distributed across multiple fluid pipeline subsystems: 3 joints in the liquid oxygen (LOX) feed system, 6 in the first-stage fuel system, 24 in the second-stage fuel system, 33 in assembly and purging lines, 118 in canalisation lines, 4 in high-frequency pressure measurement junctions, and 27 in temperature measurement nodes.

The varied operational requirements across these pipelines, are satisfied by multiple configurations of the coupling nut joint. In a semi cryogenic system alone, 11 distinct geometric configurations have been identified, each with specific design features such as lock rings, connectors, external threads, and double-nut assemblies. Specialized sealing arrangements comprise either metallic gaskets or elastomeric O-rings.

Design validation must address the coupled effects of internal fluid pressure, gasket contact stress, thermal contraction under cryogenic conditions, and the preload distribution across multiple material interfaces. Safe operation across proof, pneumatic, and operating pressure regimes must be ensured, in the absence of an international design standard for coupling-nut joints.

Objective and Scope of Work

The objective of this project is to develop a modular computational tool that automates the safety assessment and geometry optimization of coupling-nut joints according to LPSC committee design guidelines. The scope encompasses:

- Analytical modelling of preload and pre-torque calculations and stress distributions across interfaces.
- Multi-mode failure criterion implementation addressing thread shear (internal and external), bearing surface shear, tensile tearing, and lock-ring crushing.
- Thermal load analysis incorporating expansion effects at different cryogenic operating temperatures.
- Geometry optimization to identify safe design parameters meeting user-specified factor of safety requirement.
- Interactive user interface enabling parametric sensitivity study and rapid design iteration.

3. Literature Review

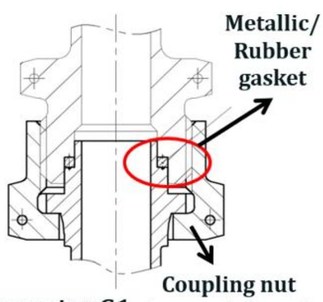
In the designing of coupling nut joints, the fundamental challenge arises from the interaction of preload (initial controlled application), pressure loading (due to fluid pressure), gasket seating (for leak proofness) and thermal effects (under cryogenic condition).

Geometric Configurations

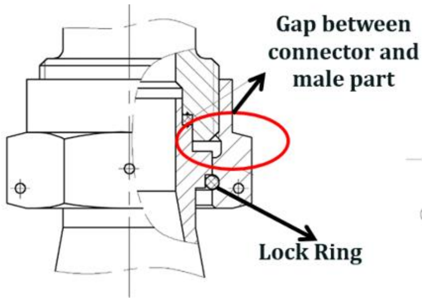
In mechanical design documentation, 11 distinct coupling-nut geometric variants have been catalogued. The primary sub-components present in coupling-nut assemblies are:

- Female nut (internally threaded coupling element)
- Connector (collar or orifice element bearing against gasket and adaptor)
- Sealing element (metallic gasket, rubber O-ring, or conical gasket)
- Lock ring (axial constraint element in certain configurations)
- Male threaded part/Adaptor (externally threaded mating component)

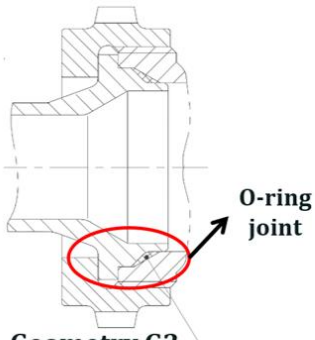
Geometric Configurations G1 through G11 are distinguished by the presence/absence of these sub-components, gasket type, thread orientation, and special features such as spherical adaptor, nut nipple assembly or double-nut assembly.



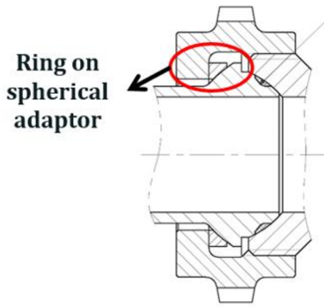
Geometry G1



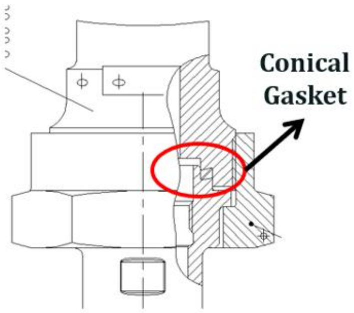
Geometry G2



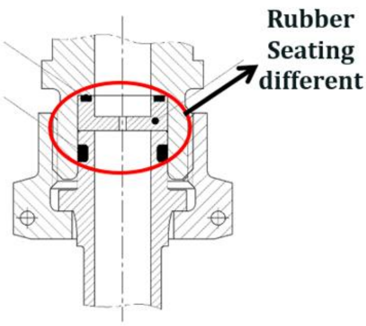
Geometry G3



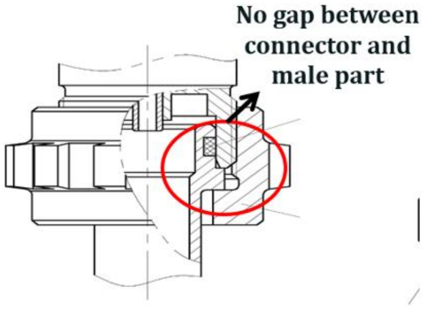
Geometry G4



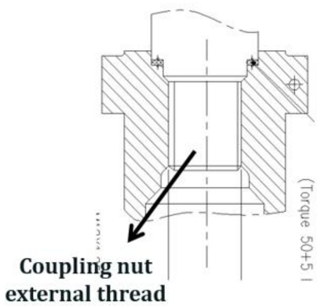
Geometry G5



Geometry G6



Geometry G7



Geometry G9

Load Classification

Committee design guidelines classify preload requirements according to three independent load types:

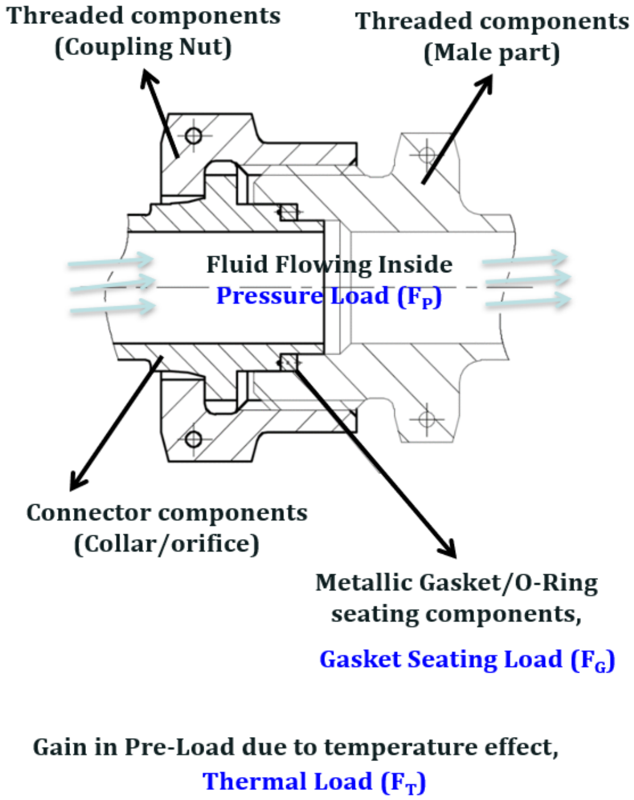


Fig. Types of Load for Preload Evaluation

Pressure Load (F_P): The axial force generated by internal fluid pressure acting on the seal area. The seal area is defined by the gasket geometry (outer diameter OD and inner diameter ID). Evaluation will be based on the proof pressure for the hydro test/maximum operating pressure (P_{max}). The proof pressure includes an inherent 1.5 pressure factor; therefore, no additional pressure factor is applied when evaluating design checks at proof pressure. When design checks are performed at ultimate tensile stress (UTS), an additional pressure factor of 2.0 is applied to account for higher strain rate at failure condition.

Gasket Seating Load (F_G): The force required to establish and maintain metallic contact (or elastomeric compression) of the sealing element. This load is computed as the product of gasket contact area and a minimum seating stress. The design seating stress is derived by multiplying the yield strength of the gasket material by a gasket factor. For metallic gaskets, a gasket factor of 1.5 is applied; for rubber O-rings, a gasket factor of 0 is used.

Thermal Load (F_T): The change in preload due to thermal expansion of joint when temperature deviates from the reference state. Under thermally relaxed conditions (free expansion), the preload requirement increases, while under constrained conditions (fixed geometry), preload remains constant while internal stresses adjust. The net deflection and equivalent stiffness are computed from the multi-component thermal expansion profile to determine the gain in preload.

Total Preload and Torque Calculation

Force and Torque against Pressure Load

Seal diameter (mm)	:	$\lceil (OD + ID)/2 \rceil = d_s$
Seal Area against pressure load (mm^2)	:	$\frac{\pi}{4} \times d_s^2 = A_P$
Load against pressure load (N)	:	$P_{\max} \times A_P = F_P$
Torque against pressure load (Nm)	:	$K_{\max} \times F_P \times d = T_P$

Force and Torque against Gasket Seating

Gasket load acting area (mm^2)	:	$\frac{\pi}{4} \times (OD^2 - ID^2) = A_G$
Gasket factor (material dependant)	:	m=1.5 or 0
Min. design seating stress (MPa)	:	$Y = m \times Y_{yt}$
Load against gasket seating (N)	:	$y \times A_G = F_G$
Torque against gasket seating (Nm)	:	$K_{\max} \times F_G \times d = T_G$

Force and Torque against Thermal Load

Net Deflection (mm)	:	$\delta = (\alpha 2L2+\alpha 3L3+\alpha 4L4-\alpha 1L1) * \Delta T$
Stiffness (N/mm)	:	$K_i = AE/L$
Equivalent Stiffness (N/mm)	:	$K = [\sum (K_i)^{-1}]^{-1}$
Gain in Pre-Load (Reaction force) (N)	:	$FR = K * \delta$

Equivalent Gain in Torque (Nm) : T_R = Kmax*FR*d

Here, subscripts 1, 2, 3, 4 refer to coupling nut, gasket, connector, and male threaded part respectively, α is the coefficient of thermal expansion, L is the component length, and ΔT is the temperature change from reference (room temperature) to operating condition.

Final Parameters

Total Torque Required (Nm) : $T_{min} = T_P + T_G + T_R$

Pre-Load against Maximum Torque (N) : $\dfrac{T_{\min}}{K_{\min} \times d} = F_{Pre}$

Pressure Load against Maximum Torque (N) : $P_{\max} \times A_P = F_P$

Total Load against Maximum Torque (N) : $(F_{pre} + C \times F_P) = F_{Total}$

The coefficient K accounts for thread surface friction and under-head bearing friction; typical values are 0.20 (maximum) and 0.15 (minimum). The stiffness constant C will be taken as a constant value 0.2, throughout the report (in accordance with guidelines).

Failure Criteria and Stress Analysis

Design checks are performed for multiple failure modes including:

Thread Shear (Internal): Failure of the coupling nut threads under combined tensile preload and shear stress. The failure criterion compares the maximum thread stress to the material yield or ultimate tensile strength, accounting for the effective thread engagement length and root area.

Thread Shear (External): Failure of the male threaded part threads under similar combined loading. The external thread geometry typically exhibits a larger root area and different stress concentration compared to the internal thread.

Bearing Surface Shear (Nut): Failure of the bearing surface of the coupling nut where it contacts the connector. This failure mode is present only in configurations where a connector component exists and transmits load directly to the nut.

Bearing Surface Shear (Connector): Failure of the connector bearing surface under compressive and shear loading from the gasket and the male part. This mode is configuration-dependent and is suppressed in designs without a connector.

Tearing at Minimum Cross-Section (Nut): Tensile failure of the coupling nut at its minimum cross-sectional area (typically at the base of the internal threads or at the annular cross-section between ID and OD). This is a tensile stress criterion applied to the weakest cross-section of the nut.

Lock-Ring Shear (Configuration-Dependent): Failure of the lock ring through radial crushing or bearing shear, applicable only in Configuration 9 where a lock ring provides axial constraint.

Each failure criterion is evaluated at two stress levels: yield strength (YS) and ultimate tensile strength (UTS), resulting in separate FoS computations. The design is considered safe when all computed FoS values exceed the minimum required threshold.

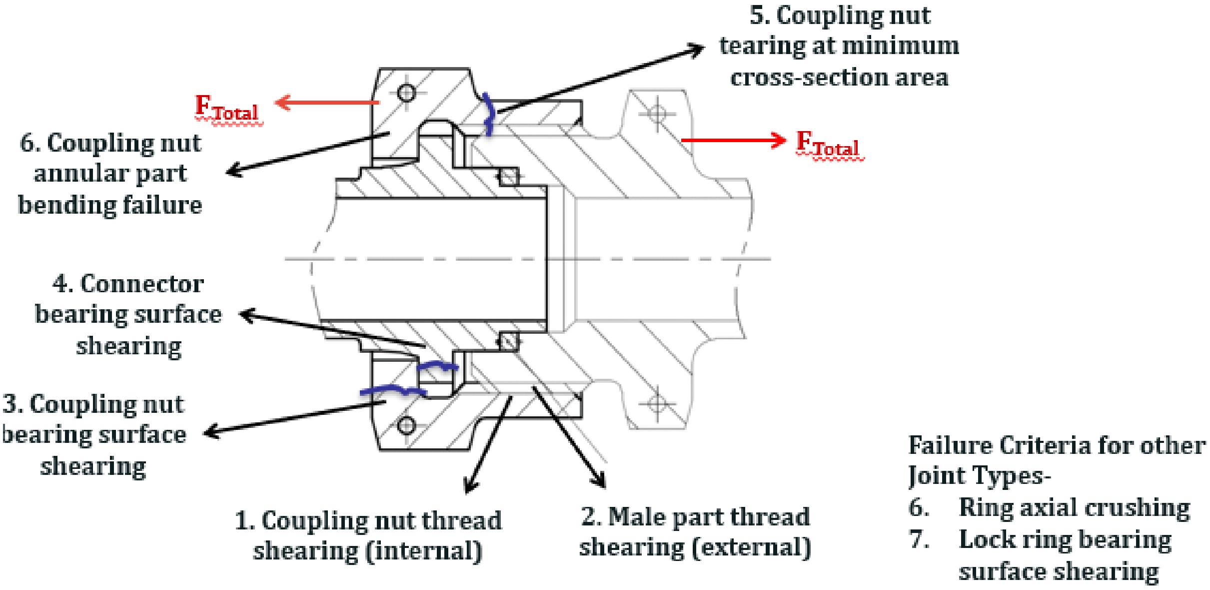


Fig. Multiple Failure Criteria

Material Properties and Thermal Effects

Materials employed in coupling-nut assemblies include:

- Coupling nut, connector, lock ring and adaptor:

  High Strength Steel (Russian austenitic stainless steel; Young's modulus ≈ 210 GPa; coefficient of thermal expansion ≈ 1.38 × 10^{-5} /°C; yield strength ≈ 882

MPa; UTS ≈ 1078 MPa)
12-10PH(high-strength steel; Young's modulus ≈ 210 GPa; CTE ≈ 9.36×10^{-6} /°C; yield strength ≈ 785 MPa)
AISI 321 (low-carbon steel; Young's modulus ≈ 186 GPa; CTE ≈ 1.56×10^{-5} /°C; yield strength ≈ 196 MPa)
15-5PH (high-strength alloy steel; Young's modulus ≈ 210 GPa; CTE ≈ 1.2×10^{-5} /°C; yield strength ≈ 980 MPa)
Titanium (alloy steel; Young's modulus ≈ 210 GPa; CTE ≈ 1.2×10^{-5} /°C; yield strength ≈ 838 MPa).

- Gasket sealing element:
  Copper (metallic gasket material; Young's modulus ≈ 113 GPa; coefficient of thermal expansion ≈ 1.7×10^{-5} /°C; yield strength ≈ 60 MPa)
  Rubber O-rings (elastomeric sealing element; negligible elastic modulus for structural load transfer; gasket factor assumed zero)

Thermal analysis incorporates the coefficient of thermal expansion (CTE), Young's modulus, component length, and temperature change (ΔT) to compute net deflection and equivalent stiffness. At cryogenic temperatures (ΔT = -203°C or -101°C), differential contraction between materials creates additional preload and internal stress redistribution. An equivalent stiffness constant of 0.2 is applied to account for load distribution across the multi-material interface.

4. Methodology

Overall Workflow Overview

The coupling-nut safety and sizing tool executes a sequential computation designed to assess baseline safety and, when required, iteratively optimize significant geometric parameters to achieve specified safety targets. The tool is implemented in two parallel workflows: a script-only analysis mode and an interactive graphical user interface (GUI) via MATLAB App Designer. Both workflows execute identical solver and analysis functions, ensuring consistency between results.

The workflow proceeds through the following steps:

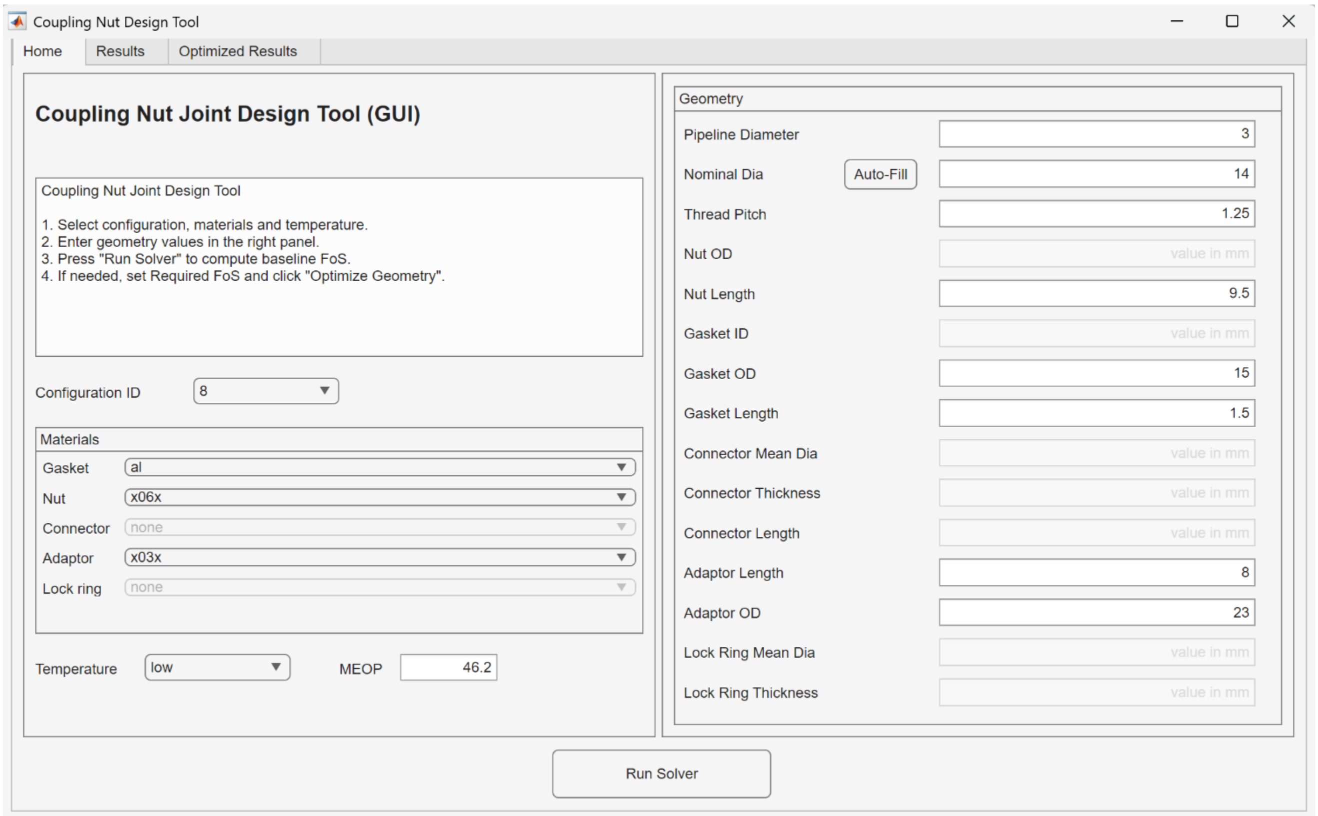
1. Configuration Selection: User specifies the geometric configuration type (1–11) from the supported portfolio of coupling-nut designs.

2. Material Selection: User selects materials for each component (gasket, coupling nut, connector, adaptor, lock ring) from a validated material database.

3. Thermal Condition Selection: User specifies operating temperature (ambient, low cryogenic, or high temperature).

4. Pressure Input: User enters the maximum operating pressure (MEOP) in MPa.

5. Geometry Input: User provides basic dimensional parameters in millimeters (nominal diameter, pitch, outer diameter, length, gasket dimensions, connector dimensions, etc.).
6. Solver Analysis: The solver computes preload, torque, and factor of safety for all applicable failure modes.
7. Safety Assessment: Minimum FoS is extracted and compared against user-specified requirement.
8. Optimization Decision: If baseline FoS meets requirement, analysis concludes; otherwise, optimization is initiated.
9. Optimized Design: Brute-force search identifies minimum geometry modifications to achieve required FoS.
10. Results Display: Baseline and optimized results are presented in tabular and graphical form.



Fig, Graphical User Interface

Analytical Formulation

The tool evaluates six distinct failure modes; each computed for both yield strength (YS) and ultimate tensile stress (UTS) conditions. For each failure mode, a factor of safety is defined as:

$$FoS_{mode} = \frac{\text{Allowable Stress}}{\text{Applied Stress}}$$

Allowable Yield shear strength at RT, MPa	:	0.57*YS
Allowable UTS shear strength at RT, MPa	:	0.57*UTS

Internal and External Thread Shear (Coupling Nut and Adaptor):

Number of threads per mm (n_t)	:	1/p
Shear area (A_{s1}), mm^2	:	$\pi n_t l_{eff} d_3 \left(0.57735(d_P - d_3) + \frac{1}{2n_t} \right)$
Shear stress due to torque applied, MPa	:	F_{total}/A_{s1}

This applied stress is used to compute, four factors of safety, two each for the coupling nut and adaptor.

Coupling nut bearing surface shear

Nut Shearing diameter (d_{s2}), mm	:	d-6 = 16
Bearing surface shear area (A_{s2}), mm^2	:	$\pi \times d_{s2} \times t_{nut} =$
Shear stress on nut bearing surface, MPa	:	F_{total}/A_{s2}

Connector bearing surface shear

Bearing surface shear area (A_{s3}), mm2	:	$\pi \times D_{Km} \times t_{Km} =$
Shear stress due to torque applied, MPa	:	F_{total}/A_{s3}

Coupling nut tearing at minimum cross-section area

Nut tearing cross-section area (A_{s4}), mm2	:	$\frac{\pi}{4} \times (d_o^2 - d_i^2) =$
Tensile stress on nut tearing c/s, MPa	:	F_{total}/A_{s4}

Lock-Ring Shear (Configuration 9 only):

Bearing surface shear area (A_{s5}), mm2	:	$\pi \times D_{lr} \times t_{lr}$
Shear stress due to torque applied, MPa	:	F_{total}/A_{s5}

Minimum FoS Identification and Optimization

The tool extracts the minimum FoS across all computed failure modes:

$$FoS_{min} = \min\{FoS_{int,YS}, FoS_{int,UTS}, FoS_{ext,YS}, FoS_{ext,UTS}, FoS_{bearing}, FoS_{tear,UTS}, FoS_{tear,YS}, FoS_{lockring}\}$$

This minimum value serves as the governing failure mode and becomes the primary optimization objective. The optimization goal is to identify geometry modifications such that:

$$FoS_{min,optimized} \geq FoS_{required}$$

Developed Code Architecture

The tool comprises six core functional modules and a main script driver:

coupling_nut_tool.m (Main Script Driver)

This script orchestrates the complete workflow: configuration selection, user input collection, function calls, optimization decision logic, and results display. The script maintains program state through MATLAB struct arrays containing geometry, materials, and result data.

load_config_rules.m (Parametric Database)

This function encodes the parametric rules for each of the 11 supported geometric configurations. It returns a configuration struct containing Boolean flags indicating the presence or absence of configuration-specific features:

- has_connector: Boolean flag; if true, connector geometry inputs are solicited and bearing surface stress is computed
- has_lock_ring: Boolean flag; if true, lock ring geometry inputs are solicited and lock-ring shear FoS is computed
- double_nut: Boolean flag; if true, geometry input is bifurcated into separate small-nut and big-nut input blocks (currently under development)
- id: Configuration identifier (1–11)

The configuration flags serve as control logic for conditional geometry input and stress calculation within the solver.

get_user_initial_geometry2.m (Geometry Input Manager)

This function manages all geometric parameter input with configuration-dependent field enablement/disablement. Key features include:

- Pipeline Diameter Input: User enters the pipeline inner diameter; the function recommends a nominal nut diameter according to the mapping: pd < 6 mm → M14; 6 ≤ pd < 8 → M18; 8 ≤ pd < 10 → M22; 10 ≤ pd < 12 → M24; 12 ≤ pd < 16 → M30; 16 ≤ pd < 20 → M33; 20 ≤ pd < 30 → M48; pd ≥ 30 → M64
- Nominal Diameter and Pitch Validation: User selects from valid nominal sizes (6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 27, 30, 33, 36, 39, 42, 45, 48, 52, 56, 60 mm) and pitches (1, 1.25, 1.5 mm)
- OD/ID Constraints: Outer diameter must exceed nominal diameter; ID is set to nominal by default (exception: Config 8 external thread sets ID = 0)
- Effective Thread Length: Computed as $l_{eff} = L - 2p$ where L is total nut length and p is pitch
- Gasket Geometry: ID < OD < nominal nut diameter constraint enforcement
- Connector Geometry: Mean diameter < nominal nut diameter constraint; wall thickness and length inputs
- Lock Ring Geometry (Config 9): Mean diameter < nominal nut diameter
- Thermal Case Geometry (when Temperature ≠ ambient): Gasket length, adaptor length, adaptor OD/ID, connector length inputs with temperature-dependent geometry rules

run_solver.m (Calculation Backbone)

This function implements the complete analytical pipeline: preload calculation, torque calculation, stress distribution across multi-material interfaces, and FoS computation for all applicable failure modes. The solver returns a result struct containing all intermediate calculations and final FoS values for each failure mode at both YS and UTS conditions.

extract_min_fos.m

This function parses the result struct, identifies all fields containing "FoS", extracts numeric (non-NaN) values, and returns the minimum FoS across all failure modes along with the complete list of FoS values for diagnostic purposes.

optimize_fos_wrapper.m

This wrapper function initiates the brute-force optimization process when baseline FoS falls below the user-specified requirement. It performs the following operations:

1. Compares baseline FoS_{min} to $FoS_{required}$; if baseline exceeds requirement, returns baseline geometry unchanged
2. Defines three primary design variables: $x(1) =$ nutOD, $x(2) =$ nut length L, $x(3) =$ connector wall thickness t_{km}
3. Establishes bounds:
    - OD: [1.05 × d_nom, 2.0 × d_nom]
    - L: [0.5 × L_baseline, 3.0 × L_baseline]
    - t_km: [0.5 × t_km_baseline, 3.0 × t_km_baseline]
4. Invokes fminsearch algorithm with tolerance settings TolX = 1e-3, TolFun = 1e-3
5. Rebuilds geometry struct from optimized parameters, recomputes derived dimensions (effective thread length, wall thickness, connector ID)
6. Executes final solver run and reports optimized FoS and geometry

objective_fos.m (Cost Function for Optimization)

This function computes the cost function for the optimization algorithm:

$$cost = \max\left(0, FoS_{required} - FoS_{achieved}\right)$$

The function receives candidate design variables, enforces bounds through penalty methods (returns 1e6–1e9 for infeasible geometries), constructs the geometry struct, calls the solver, extracts minimum FoS, and returns the cost. The fminsearch algorithm iteratively adjusts design variables to drive cost toward zero, signifying achievement of the FoS requirement.

Input/Output Data Structure

Inputs to the Tool:

- Configuration ID (1–11)
- Material selection for 5 components (gasket, nut, connector, adaptor, lock ring)
- Temperature regime (ambient, low, high)
- MEOP pressure (MPa)
- Geometric parameters (nominal diameter, pitch, OD, ID, lengths, connector dimensions, gasket dimensions, etc.)
- User-specified required FoS (only if optimization is needed)

Outputs from the Tool:

- Baseline FoS values for all applicable failure modes (YS and UTS)
- Minimum governing FoS and corresponding failure mode identifier
- Torque calculations: pressure torque, gasket torque, thermal torque, total torque
- Preload calculations: pressure preload, gasket preload, thermal preload, total preload
- (If optimization triggered): Optimized geometry parameters and corresponding optimized FoS values
- Convergence plot (iterations vs. achieved minimum FoS)

5. Test Run / Numerical Validation

Test Case: Configuration 8 (External Threaded Coupling Nut)

A representative validation case was executed using Configuration 8 (external threaded coupling nut) under cryogenic operating conditions (low temperature, $\Delta T = -203$ °C). This configuration represents a specialized joint design used in certain high-pressure measurement and drain system applications.

Input Parameters

Parameter	**Value**	**Unit**
Configuration	8	—
Pipeline Diameter	3.0	mm
Recommended Nominal Diameter	M14	—
Nominal Diameter (User Selected)	14.0	mm
Thread Pitch	1.25	mm
Nut OD	14.0	mm
Nut ID	0	mm (Config 8 rule)
Nut Length	9.5	mm
Gasket Material	Aluminum	—
Gasket ID	14.0	mm
Gasket OD	15.0	mm
Gasket Length	1.5	mm
Nut Material	X06x	—
Adaptor Material	X03x	—
Adaptor OD	23.0	mm
Adaptor Length	8.0	mm
Temperature	Low (Cryogenic)	—

Parameter	Value	Unit
MEOP	46.2	MPa
Pressure Factor	1.1	—
Maximum Pressure (Pmax)	50.82	MPa

Baseline Analysis Results

Configuration 8 is characterized by the absence of a connector component and an external thread geometry on the coupling nut. As a result, connector bearing surface shear, nut bearing surface shear, and tearing failure modes are not applicable; these fields return NaN.

Failure Mode	FoS Value	Stress Level	Status
Internal Thread Shear	8.9081	Yield	Computed
Internal Thread Shear	10.6988	Ultimate	Computed
External Thread Shear	7.1356	Yield	**Governing Mode**
External Thread Shear	8.4536	Ultimate	Computed
Bearing Surface (Nut)	NaN	—	Not Applicable
Bearing Surface (Connector)	NaN	—	Not Applicable
Nut Tearing	NaN	—	Not Applicable
Lock Ring Shear	NaN	—	Not Applicable

The computed effective thread engagement length was $l_{eff} = 9.5 - 2 \times 1.25 = 7.0$ mm.

Optimization with Required FoS = 9.0

The user specified a required factor of safety of 9.0, which exceeded the baseline minimum of 7.1356. The optimization wrapper was invoked to identify minimum geometry modifications.

Parameter	**Baseline**	**Optimized**	**Change**	**Percent Change**
Nut OD	14.0000 mm	15.0108 mm	+1.0108 mm	+7.2%
Nut Length (L)	9.5000 mm	28.0186 mm	+18.5186 mm	+195.0%
Effective Thread Engagement (l_eff)	7.0000 mm	25.5186 mm	+18.5186 mm	+264.6%
Connector Thickness	N/A	N/A	—	—
Gasket ID/OD	14.0 / 15.0 mm	14.0 / 15.0 mm	—	(Unchanged)
Adaptor Geometry	Unchanged	Unchanged	—	(Unchanged)

After optimization, the following FoS values were achieved:

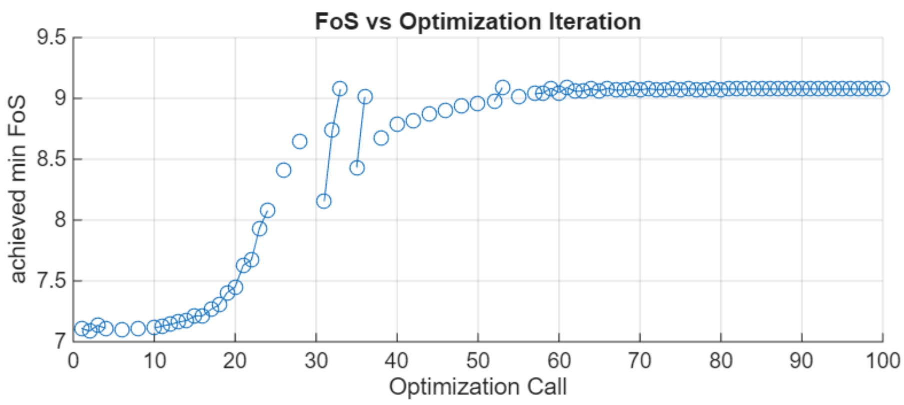
Failure Mode	**Baseline FoS**	**Optimized FoS**	**Improvement**
Internal Thread Shear (YS)	8.9081	11.3318	+27.3%
Internal Thread Shear (UTS)	10.6988	13.6098	+27.2%
External Thread Shear (YS)	7.1356	9.0770	+27.2%
External Thread Shear (UTS)	8.4536	10.7537	+27.2%

Optimized Minimum FoS: 9.0770 ≥ required 9.0 ✓

The optimization successfully achieved the specified safety requirement with a uniform ~27% improvement across all failure modes.

Convergence Behavior and Iteration Analysis

The optimization execution was monitored over 100 function evaluations (optimization calls). The convergence plot revealed the following pattern:



- Phase 1 (Calls 1–15): Rapid improvement in minimum FoS, rising steeply from 7.0 to 8.5
- Phase 2 (Calls 15–40): Continued but decelerating improvement, reaching ~9.0 by call 35
- Phase 3 (Calls 40–100): Plateau and stability, with minimum FoS hovering at 9.0–9.2

The characteristic shape reflects fminsearch brute-force exploration of the parameter space. The non-smooth oscillations in the middle phase indicate that the algorithm explores local variations in the constraint surface (different failure modes transitioning as governing). Convergence to the target FoS requirement (9.0) was achieved by approximately 40 optimization calls, with solution stability thereafter.

Input Field Management Validation

The GUI implementation was validated across multiple configurations to confirm correct field enablement/disablement:

Configuration 8 (External Thread):

- Connector fields: Disabled (shown as "none") ✓
- Lock ring fields: Disabled (shown as "none") ✓

- Bearing surface calculation: Suppressed (NaN results) ✓
- Tearing calculation: Suppressed (NaN results) ✓

Configuration 9 (with Lock Ring) (representative, not detailed herein):

- Lock ring fields: Enabled and solicited ✓
- Lock ring FoS calculated: Active ✓

Temperature-Dependent Geometry (Low Temperature):

- Gasket length field: Enabled ✓
- Adaptor length field: Enabled ✓
- Adaptor OD/ID rules: Applied ✓

Auto-Fill Nominal Diameter Recommendation

The pipeline diameter auto-fill feature was validated with the following test case:

Pipeline Diameter (mm)	**Recommended Nominal**	**M6–M60 Valid Range**
3.0	M14	✓ ($6 \leq 14 \leq 60$)
5.5	M14	✓
7.0	M18	✓
9.0	M22	✓
11.0	M24	✓
15.0	M30	✓
19.0	M33	✓
25.0	M48	✓
32.0	M64	✓

All recommended nominal diameters fell within the valid M6–M60 range and aligned with pipeline diameter requirements.

Known Limitation: Configuration 10 (Double Nut Joint)

Configuration 10 (double-nut assembly with small and large nut components) is currently non-functional and under investigation. The dual-nut input block geometry parsing and corresponding FoS evaluation logic requires debugging. As of the present report, Config 10 is documented but not operationally available. Users must select Configurations 1–9 or 11 for production use.

6. Results and Discussion

Key Findings

The development and validation of the coupling-nut safety and sizing tool has yielded several significant results:

Brute-Force Optimization Convergence

The fminsearch-based optimization converged to the specified FoS requirement (9.0) within ~40 iterations and maintained solution stability to 100+ iterations. The three primary design variables (nut OD, nut length, connector wall thickness) demonstrated clear coupling: nut length was the dominant driver of thread stress reduction, while OD provided secondary margin. The primary driver of geometry change was the substantial increase in nut length, which distributed the preload across a longer engagement region, thereby reducing stress concentration.

Applicability to Multi-Material Assemblies

The successful analysis of coupling-nut joints(which combine up to five distinct materials with different properties) demonstrates the tool's capability for general multi-material aerospace interface problems. The methodology is directly extensible to flange joints, which share similar multi-material contact and preload distribution characteristics.

Effective Thermal Load Modeling

The thermal load calculation properly accounts for differential contraction of multi-component assemblies at cryogenic temperatures. In the test case, the gasket, connector, and male threaded part all exhibited lower coefficients of thermal expansion than the coupling nut (High Strength Steel), resulting in net contraction that altered preload distribution. The equivalent stiffness approach enabled rapid calculation of this effect without detailed finite-element analysis, maintaining tool usability.

Limitations and Sources of Uncertainty

The tool operates within the following limitations:

1. Analytical Stress Formulation

The stress calculation uses simplified formulas derived from committee guidelines rather than detailed finite-element analysis. Thread root stress, for example, is computed from effective area and preload without explicit 3D stress concentration factors. This approach is conservative (intentionally over-predicts stress to yield lower FoS values) but may overestimate stress in complex geometries.

2. Material Nonlinearity

The tool assumes linear elastic behaviour and does not account for plastic yielding, strain hardening, or creep under sustained cryogenic preload. At cryogenic temperatures, austenitic stainless steels generally remain ductile, but the assumption of constant yield strength may be violated.

3. Gasket Seating Assumption

The gasket seating load calculation assumes that a metallic gasket factor of 1.5 adequately captures the seating requirement. Gasket seating depends on surface finish, material hardness, and contact pressure. The rubber O-ring gasket factor of 0 assumes no additional preload needed but does not account for squeeze relaxation over time.

4. Configuration 10 Incompleteness

Double-nut joint analysis is not currently implemented due to unresolved geometry parsing logic.

5. Pressure Factor Application

The pressure factor (1.5 at proof, 2.0 at UTS) is applied uniformly across all components and failure modes. Component-specific pressure factors may differ based on material constitutive behaviour.

6. Discrete Material Database

The material selection is restricted to a finite menu of pre-validated alloys. New materials require manual database entry and re-validation, limiting tool extensibility.

Challenges

Objective Function Non-Convexity

The cost function for optimization exhibits non-smooth behavior as different failure modes alternate in governing role. The brute-force approach handles this non-convexity robustly, but convergence can be slow in high-dimensional design spaces (current implementation uses 3 primary variables; future extensions may require more).

Bounds Selection

The optimization bounds (OD: 1.05–2.0× nominal, L: 0.5–3.0× baseline, t_km: 0.5–3.0× baseline) are heuristic. Tighter or broader bounds could accelerate convergence but require engineering judgment for each configuration.

Material Property Temperature Dependence

Material properties (yield strength, modulus, CTE) are treated as constants. In reality, these properties vary with temperature, particularly at cryogenic temperatures. The current tool uses room-temperature yield strength with a pressure factor multiplier as a proxy for temperature effects, which is conservative but approximate.

7. Conclusion

This project has delivered a comprehensive computational tool for safety assessment and geometry optimization of coupling-nut joints in cryogenic propulsion systems.

The tool successfully:

- Computes preload, torque, and stress distributions per committee formulae
- Extracts minimum FoS across all applicable failure modes
- Identifies geometry modifications optimizing to user-specified safety requirements within ~40 iterations
- Manages 11 geometric configurations with conditional field enablement
- Provides auto-fill guidance for nominal diameter selection based on pipeline diameter
- Maintains computational performance suitable for interactive GUI operation

Scope for Future Work

1. Debugging

Resolve geometry parsing logic for double-nut joint assembly (Configuration 10) and implement full FoS evaluation for both nut components.

2. Finite-Element Validation

Compare stress predictions against detailed 3D FEA models and calibrate correction factors.

3. Material Database Expansion

Incorporate additional material properties (temperature-dependent yield strength, CTE, modulus) and extend the materials to include new alloys.

4. Thermal Stress Mapping

Develop transient thermal analysis to map temperature fields in the joint assembly and compute corresponding stress distributions. This will improve thermal load modelling beyond the current approach.

5. Extension

Extend the methodology to flange joints and other multi-material aerospace interfaces, creating a generalized tool framework for safety assessment of complex fastening systems.

Conclusion

I am grateful for the opportunity to complete this one-month training at the Liquid Propulsion Systems Centre (LPSC), ISRO, which provided valuable exposure to the design and analysis of cryogenic propulsion system components. During this period, I significantly strengthened my understanding of liquid rocket propulsion fundamentals, including engine thermodynamic cycles, propellant feed systems, and the functional role of structural and flow-control elements in rocket engines.

The training offered hands-on experience in the design, analysis, and validation of critical subsystems and interface elements associated with cryogenic engines. Working closely with scientists, engineers, technicians, and support staff helped me develop professional communication skills and an appreciation for interdisciplinary collaboration in large-scale engineering programs.

Through this work, I enhanced my technical skills in engineering analysis and simulation using tools such as **ANSYS (Structural and Fluent), MATLAB, and CAD software including SolidWorks**. These tools were applied to real engineering problems involving structural integrity, fatigue assessment, and flow characterization, bridging the gap between theoretical knowledge and practical implementation.

Overall, this training has strengthened my foundation in propulsion system design and analysis and has increased my confidence in applying these skills to future research and engineering challenges in the field of aerospace propulsion.