THE UNIVERSITY OF QUEENSLAND

Preliminary Design of a Hypersonic Impulse Facility
X4 Expansion Tunnel

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In memory of my grandfather

Shizhu Fu

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Abstract

Due to the relocation of X3 Expansion Tube Facility at The University of Queensland, a large lab space availability permitted the development of a new Expansion Tunnel possibily named X4, which will be targeting only on high enthalpy planetary entry flows.

This project aims to perform the frontier exploration of investigating the possibilities of X4 expansion tunnel. This encouraging exploration includes:

- Investigation into other facilities around the world;
- Review of significant theories for a preliminary expansion tunnel facility design;
- Determination of the design guidelines;
- Development of a tool to assist the future design team;
- Integrating vital analytical models into the design tool;
- Delivering several sets of X4 design with demonstration drawings given;
- Performing a cost model study of the new facility.

With the support of expansion tunnel design theories and analytical methods, a tool named Free-piston Expansion Tube Calculator was developed by the author, which comprised of the following modules being able to assist a conceptual design of a Free-piston Expansion Tube:

- Dimension Calculator;
- Tube Wall Thickness Calculator;
- Necessary Piston Mass Calculator;
- Necessary Inertial Mass Calculator;
- Rough Cost Calculator.

By using the tool, two sets of X4 design with proposal scale of 40-meter and 60-meter were delivered and the results are summarised in Case Study 1 and Case Study 2. Besides implementing designing tasks, this Python based program was also used to complete a study of influence on permitted piston mass by varying single and dual operation condition variables.

Furthermore, a study of facility material cost versus facility scale was done by combining the core codes from 5 modules of the program, the results of which showed that the facility raw material cost had an exponential increasing trend as facility scale going up, The curve fitted mathematical model to explain this increase is Cost = a*exp(b*Scale) where a = 29.75 with range in (29.14, 30.35) and b = 0.05981 with range in (0.05945, 0.06018). The facility material cost study also indicated that the driver cost could gradually take a larger proportion to the facility overall cost, which is from 17.3% to 21.65%.

Key Words

expansion tunnel, expansion tube, free-piston driver, design, hypervelocity impulse facility, hypersonic, ground testing facility, software development, shock tunnel

Australian and New Zealand Standard Research Classifications (ANZSRC)

120404 Engineering Systems Design (40%)

080306 Open Software (30%)

090107 Hypersonic Propulsion and Hypersonic Aerodynamics (30%)

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Nomenclature

Subscripts

* - Throat between compression tube and shock tube

0 – Initial value, stagnation condition

A – reservoir gas

D – Driver

R – Reflected

Dimension

D – Compression tube diameter

A – Area of compression tube

L – Length between piston and primary diaphragm while x is the variable

A^* – Area at entrance from compression tube to shock tube

d – Diameter of shock tube

Reservoir

γ_A – Ratio of specific heat, reservoir gas

$a_{A,0}$ – Speed of sound, reservoir gas

$p_{A,0}$ – Reservoir gas pressure

Piston

u – Piston velocity

a – Piston acceleration

Behind Piston

γ_A – Ratio of specific heat, gas behind piston

a_A – Speed of sound, gas behind piston

p_A – Gas pressure behind piston

M_R – Reflected shock Mach number

In front of piston

γ_D – Ratio of specific heat, driver gas value

a_D – Speed of sound, driver gas value

p_D – Pressure, driver gas value

In shock tube (throat)

γ_* – Ratio of specific heat, throat gas value

a_* – Speed of sound, throat gas value

p_* – Pressure, throat gas value

Behind reflected shock (behind piston)

γ_A – Ratio of specific heat, reservoir gas

$a_{A,R}$ – Speed of sound, reservoir gas

$p_{A,R}$ – Reservoir gas pressure

Greek

ρ – Density

Δ – Change in Value

λ – Compression Ratio

β – Over-driving Factor

σ – Stress

μs – Millisecond

Acronyms and Abbreviations

UQ – The University of Queensland

L1d – 1-Dimension Lagrangian transient compressible flow solver

GUI – Graphical User Interface

AUD – Australian Dollar

X4 – X4 Expansion Tube Facility or X4 Expansion Tunnel

ms – Microsecond

Chapter 1 Introduction

1.1 Background

This thesis project delivers a conceptual design of a new expansion tunnel facility possibly named X4 to be placed in the Hypersonic X-lab of UQ.

A large space in UQ's Hypersonic Expansion Tube Lab is available because of the relocation of the X3 Expansion Tube facility, which offers the possibility to develop a new facility. One vital requirement is that X4 will target high enthalpy planetary entry flows without targeting the scramjet experiments to be suitable for running in university environment.

There are currently two expansion tubes being operated at UQ - the X2 and X3, which are both free-piston driven hypervelocity impulse facilities having the ability to implement hypersonic research including simulating planetary entry flows and scramjet engine development [1] [2].

Thus, plans were discussed for a relatively intermediate-sized facility (X4) to be more suitable in university environment with building above X2's capabilities, while avoiding the challenges of operating a facility of X3's shear-scale.

1.2 Objectives

Communications with researchers/scientists within the research group indicated that the design delivered by this thesis would not be a specific construction plan because there would be a team to perform the actual design. Thus, this thesis aims to deliver the most frontier exploration of investigating the possibilities of X4 expansion tunnel.

This encouraging exploration includes:

- Investigation into other facilities around the world;
- Review of significant theories for a preliminary expansion tunnel facility design;
- Determine the design guidelines;
- Develop a specific tool to assist the future design team (e.g. a computer program);
- Integrate vital models into the design tool;
- Deliver a demonstration design of X4;
- Perform a cost model study of the new facility.

1.3 This Thesis

This thesis has eleven body chapters. Chapter 1 is a brief introduction for this project. Information of other chapters is summarised below:

Chapter 2 and 3 are typical literature review parts for a research project with different emphasized points. Chapter 2 aims to conduct a thorough but concise investigation into other hypervelocity impulse facilities especially expansion tunnels and free-piston shock tunnels. Dimension information and how the dimension would influence facility performance are important review directions.

Chapter 3 is a section to review theories for designing a free-piston driven expansion tunnel, significant information from which helped to construct a design guideline summarised in Chapter 4 to help the designer fully understand the derived design requirements.

Chapter 5 introduces a computer program developed the author coded by Python programming language. This program is a beneficial tool to explore the varied possibilities of X4, which would significantly assist the future X4 design team. This program has five modules which are:

- Dimension calculation;
- Tube wall thickness calculation;
- Necessary piston mass determination;
- Necessary inertial mass determination;
- Rough cost model.

Chapter 6 – 9 are case studies based on the design tool introduced in Chapter 5. Chapter 6 and 7 respectively deliver a set of design with different scales. Chapter 8 is another case study to investigate the single and dual variables influence on necessary mass especially the reservoir filling pressure. Chapter 9 is a study on the relationship between cost and facility scale.

Chapter 10 contains the conclusion and related discussion for this thesis.

Chapter 2 Investigations into Hypervelocity Impulse Facilities

This chapter reviewed some hypervelocity experimental facilities around the world with important information and specifications respectively summarised.

In the final section of this chapter, a comprehensive summary and comparison of reviewed facilities will be demonstrated in the form of tables. This review will be mainly focusing on the relationship between dimension and facility performance to provide design guidance to the proposal development of X4.

2.1 Shock Tunnel and Expansion Tunnel

Expansion tube facilities (Expansion tunnels) and shock tunnels are significant test tools for high-speed ground experimental studies and flight tests in the regime of hypersonic.

Shock tunnel is one of the most widely used hypervelocity impulse facilities with the following sections to be normally comprised of:

- Reservoir;
- Driver;
- Driven tube;
- Nozzle;
- Test section.

Expansion tube has a similar overall structure while the significant difference between shock tunnel and expansion tunnel is the addition of an acceleration tube which lets gas within expansion tunnel be able to have an acceleration and unsteady expansion process to reach higher total enthalpy at facility test section.

Theoretically, expansion tubes could produce a wide range of high enthalpy flow conditions [1]. The concept of expansion tube was initially proposed by Resler and Bloxom in 1952 [1, 3]. The analytical method to predict the performance of expansion tubes was established by Trimpi who also named this kind of facility [4].

2.2 Free-piston Driven Expansion Tube

The University of Queensland would be the first research institute using a free-piston driver to power an expansion tube because of Professor Stalker’s genius invention of free-piston driver after years of lost traction on expansion tube development in the 1980s around the world [1]. After more than half century of development, free-piston expansion tubes have now been an extremely vital facility to implement ground experimental tasks for hypersonic research.

Figure 1 is a schematic diagram to explain the complex wave process of a free-piston-driven expansion tube (longitude scale greatly compressed)[5].

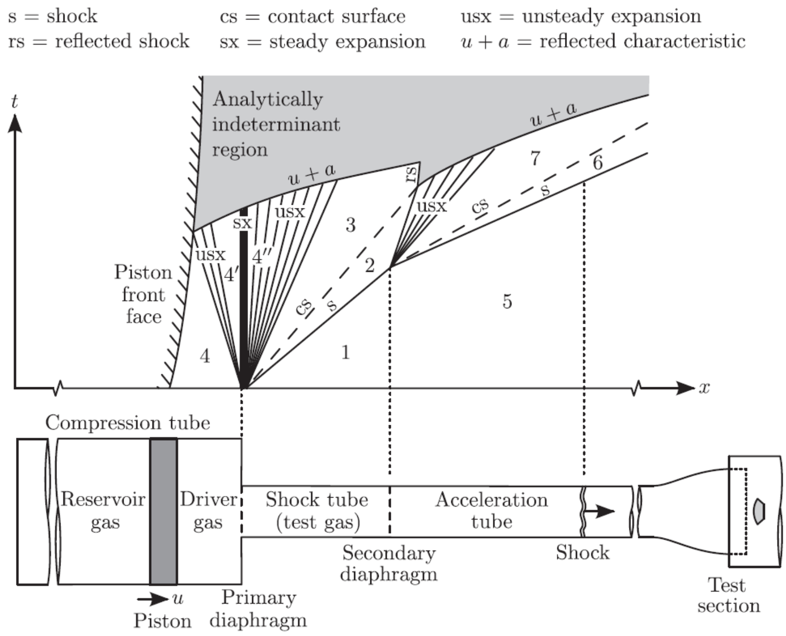


Figure 1. Idealised distance-time schematic of expansion tube flow processes (taken from [5]) (scale compressed)

2.2.1 Expansion Tubes at UQ

The University of Queensland first started experimental activities with free-piston driven expansion tube facilities in the 1980s while two facilities (X2 and X3) are still in operation. Until now, four progressively larger expansion tubes have been developed at UQ, which are summarised below [1].

- TQ: NASA Langley contracted UQ for free-piston driver's technical verification;
- X1: A modification of TQ;
- X2: Developed by Professor Morgan in 1995 and still in operation;
- X3: Developed by Professor Morgan in 2001 and still in operation [6];

TQ was world's first free-piston driven expansion tube while TQ/X1 was very successful pilot studies to establish proof-of-concept [1]. During years of operation experiences of expansion tubes at UQ, scientific evidence and research results indicate that size is paramount for expansion tubes: a longer tube provides more test time and a larger tube diameter suits testing of larger models [1]. For example, X3's scale allows much larger models to be tested with longer effective test times than X2 (test time: typically, over 1 millisecond (ms) to X3 and 500 – 100 microseconds (μs) for X2).

Development of X4 as an addition to this X-series is being discussed while this thesis presents a conceptual and preliminary design.

The following Figure 2 gives a scaled demonstration of the X-series expansion tubes facilities of The University Queensland.

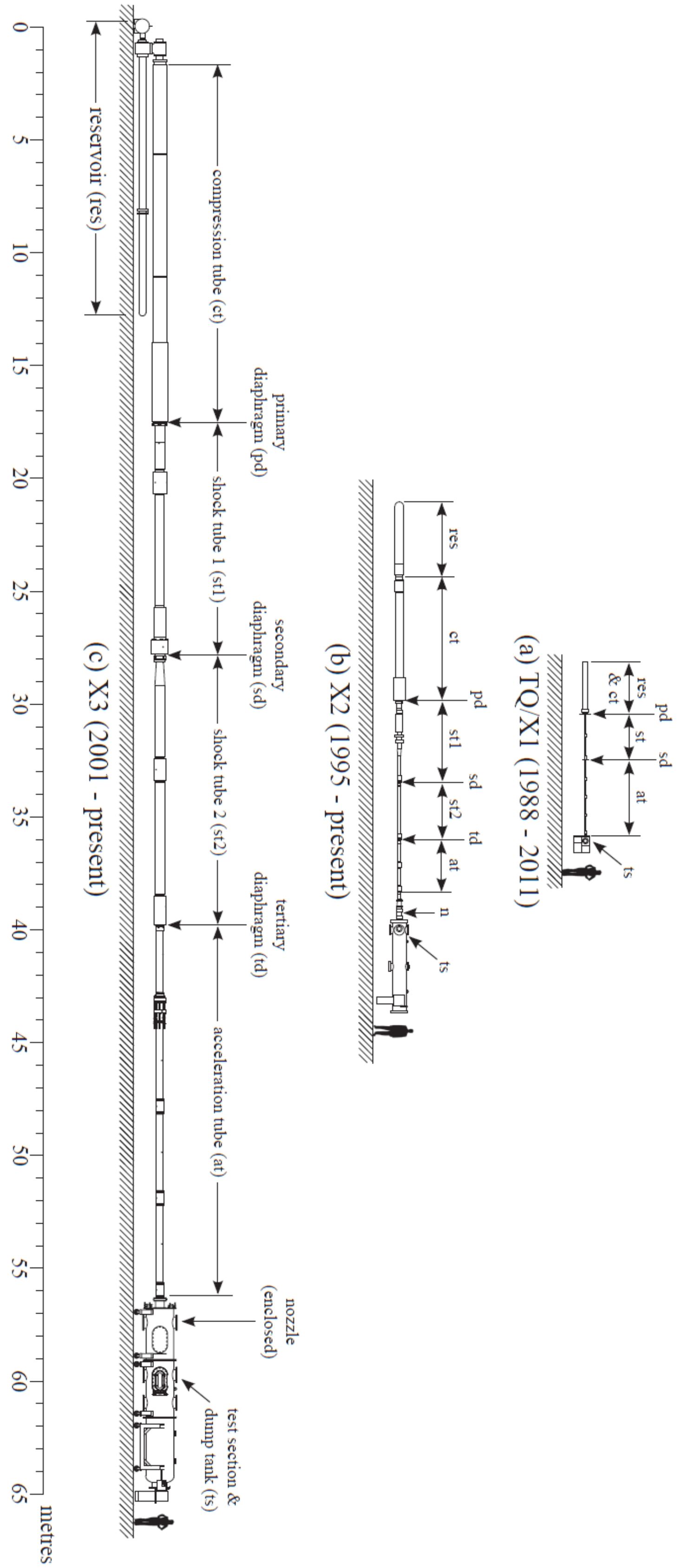


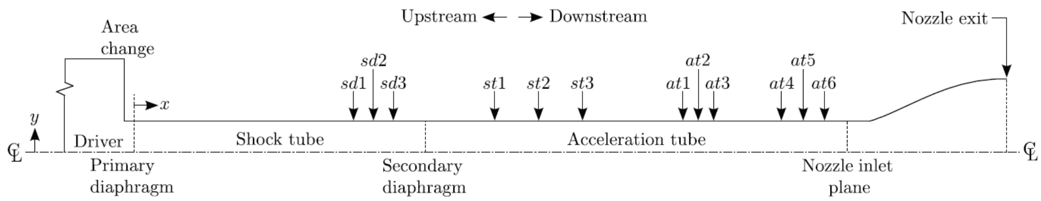
Figure 2. X-series expansion tube facilities (Scaled demonstration, taken from [1])

2.2.2 X2 Expansion Tube

The above Figure 2 (b) is a scaled demonstration of X2 Expansion Tube. Comparing with all other expansion tubes in the world, X2 is a medium-sized facility being able to be manually and conveniently operated by human without mechanical assistance. It is an economical platform to verify new ideas and technologies for research in this field. Specifications of X2 are summarised below:

- Compression tube: Diameter 256.8 mm; Length 3.8 m;
- Shock tube: Diameter 85 mm; Length 3424 mm;
- Acceleration tube: Diameter 85 mm; Length 5155mm;
- Total length: 23 m;
- Test time: typically, 50 – 100 microseconds (μs);
- Piston: 35 kg in 2006 by Scott [7]; 10.5 kg in 2010 by Gildfind in 2010 [8].

The latest geometric layout of X2 with Mach 10 mozzle is given in the Figure 3 below. This figure gives details of geometric information downstream of the primary diaphragm with longitudinal scale compressed for better demonstration.



Description	x, mm	y, mm
Driver area change	−110	-
Primary diaphragm downstream face	0	-
Transducer $sd1$	2, 577	42.5
Transducer $sd2$	2, 810	42.5
Transducer $sd3$	3, 043	42.5
Secondary diaphragm downstream face	3, 418	-
Transducer $st1$	4, 231	42.5
Transducer $st2$	4, 746	42.5
Transducer $st3$	5, 260	42.5

Description	x, mm	y, mm
Transducer $at1$	6, 437	42.5
Transducer $at2$	6, 615	42.5
Transducer $at3$	6, 796	42.5
Transducer $at4$	7, 590	42.5
Transducer $at5$	7, 846	42.5
Transducer $at6$	8, 096	42.5
Nozzle inlet plane	8, 343	-
Nozzle exit	9, 969	100.8

Figure 3. Geometric layout of X2 with Mach 10 nozzle, 2018. (Taken from [5])

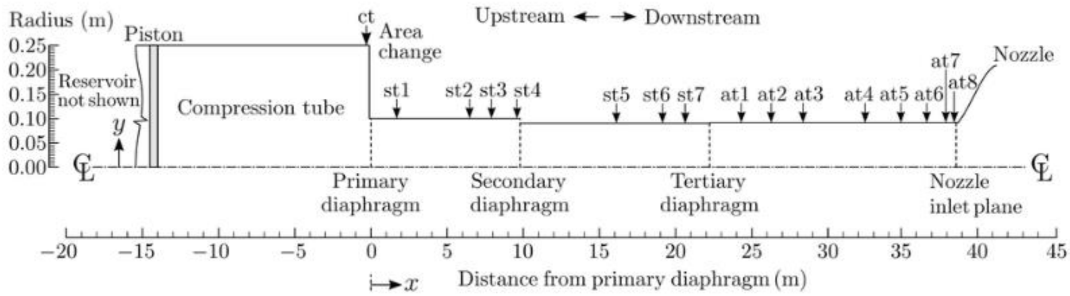
2.2.3 X3 Expansion Tube

X3 is functionally similar to X2 but at a much larger size (67 m total in length). The above Figure 2 (c) is a scaled demonstration of X3 Expansion Tube. Comparing with all other expansion tubes in the world, X2 is a very large facility (total length around 70 meters) which requires mechanical assistance for operation. The development of a reflected shock tunnel operating mode for X3 is being applied in recent years, which are expected to place significant strain on the maintenance and operation of the facility [2].

Specifications of X3 are summarised below:

- Compression tube: Diameter 500 mm; Length 14 m;
- Driven tube: Diameter 200 mm; Length 10 m;
- Shock tube: Diameter 180 mm; Length 12 m;
- Acceleration tube: Diameter 85 mm; Length 25 m;
- Test time: 1 millisecond for Mach 10 and 12 flow conditions;
- Pison: 200 kg before 2015; 100.8 kg commissioned in 2015 (designed by Gildfind and Professor Morgan et al. [REF]);
- Total length: 67 m.

The Figure 4 below demonstrates a scale-compressed Geometric layout of X3 Expansion Tube facility.



Description	x (m)	y (m)
Piston front face	−14.022	-
Transducer ct	−0.200	0.250
Driver area change	−0.100	-
Primary diaphragm	0	-
Transducer st1	1.649	0.100
Transducer st2	6.504	0.100
Transducer st3	7.955	0.100
Transducer st4	9.519	0.100

Description	x (m)	y (m)
Secondary diaphragm	9.772	-
Transducer st5	16.123	0.090
Transducer st6	19.217	0.090
Transducer st7	20.715	0.090
Tertiary diaphragm	22.237	-
Transducer at1	24.307	0.0913
Transducer at2	26.336	0.0913
Transducer at3	28.365	0.0913

Description	x (m)	y (m)
Transducer at4	32.430	0.0913
Transducer at5	34.894	0.0913
Transducer at6	36.494	0.0913
Transducer at7	38.095	0.0913
Transducer at8	38.524	0.0913
Nozzle inlet plane	38.599	-
Nozzle exit plane	41.148	-

Figure 4. Scale-compressed geometric layout of X3 expansion tube (taken from [5])

X3 currently is only used for Mach 10 and Mach 12 scramjet ground testing while using X3 to conduct high-enthalpy re-entry experiments is under development (the test time is around 1 millisecond with both flow conditions) [5].

2.2.4 JX-1

JX-1 Expansion Tube is a small-scale free-piston expansion tube commissioned at the Shock Wave Research Centre, Institute of Fluid Science, Tohoku University, Japan.

Important dimension information of JX-1 is summarised below:

- Compression tube: Bore 150 mm; Length 3 m;
- Shock tube: Bore 50 mm; Length 1.8 m;

- Acceleration tube: Bore 50 mm; Length 3.6 m;
- Total length: 13.6 m;

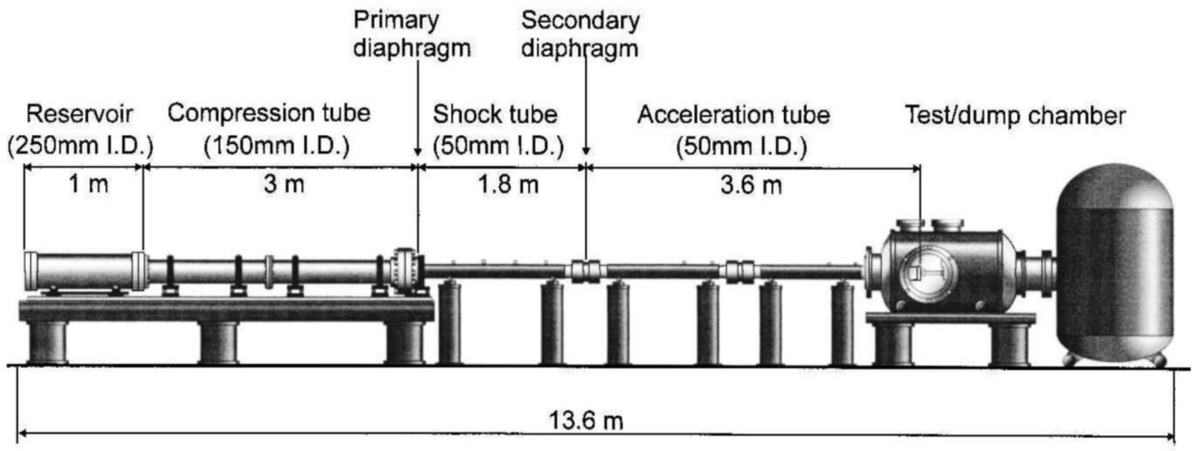


Figure 5. Schematic diagram of JX-1 expansion tube (taken from [ref])

In 2001, Ssasoh and Ohnishi et al. [REF] verified that JX-1 could reach 37 MJ/kg and 31 MJ/kg stagnation enthalpies with a test time of 13 μs and 22 μs (error allowance considered).

JX-1 was initially designed to test MUSES-C re-entry capsule in 2001 and for investigations into test time evaluation and flow quality related issues. Comparing with the proposal X4 expansion tube, JX-1 is a much smaller facility in dimension.

2.2.5 HEK-X

HEK-X is a free-piston driven expansion tube facility located in JAXA Kakuda Japan built above similar theories and principles of X2 and X3. The Figure 6 below is a schematic demonstration of this research facility.

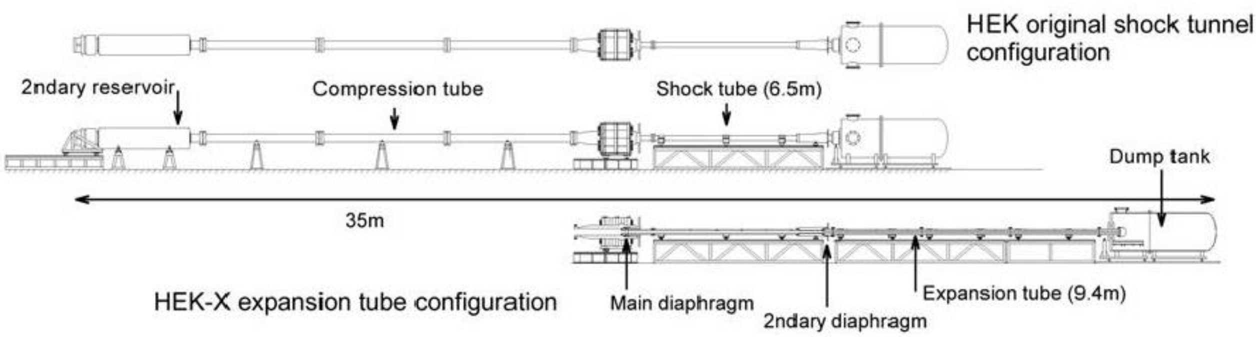


Figure 6. HEK-X Expansion Tube Facility (adapted from [9])

Specification of HEK-X are summarised below [9] [10]:

- Compression tube: Bore 210 mm; Length 16 m;

- Shock tube: Bore 72 mm; Length 6.5 m;
- Expansion tube: Bore 72 mm; Length 9.4 m;
- Total length: 35 m;
- Design maximum pressure: 130 MPa for compression tube, shock tube and expansion tube; 10 MPa for reservoir;
- Normal operation pressure: Reservoir pressure around 5.5 MPa; Compression tube around 92.4 kPa (operation conditions given in [10]);
- Flow Velocity: Max 14 km/s;
- Max Enthalpy: 25 MJ/kg;
- Piston mass: 15.7 kg in 2016 [9]; 21.33 kg in 2019[10];

The purpose of HEK-X was to implement studies of Japanese re-entry capsules in sample and scaled-model. HEK-X was built above medium-sized HEK free-piston shock tunnel which was constructed to develop large-scale free-piston shock tunnel HIEST. The original HEK shock tunnel (Figure 5) can generate up to 20 MJ/kg stagnation enthalpy with test duration of 1 millisecond [9].

HEK-X has been used for research in several fields, for example, the research of study of overdrive operation, test time evaluation and suborbital afterbody heating of sample return capsule etc...

One vital characteristic of JAXA HEK-X is a special feature of this facility - 'overdrive operation', which lets the driver gas pressure keep almost constant during the effective test period after primary diaphragm rupture. This overdrive operation has more successfully avoided shock speed reduction in the shock tube and the expansion tube with increased stagnation condition or extended test duration than other conventionally operated free-piston impulsive facilities [HEX-K 2016].

The latest research results of HEK-X indicate that the test air velocity reached 6.5 km/s at a shock wave velocity of 7.8 km/s with 20 μs test time using a method newly-developed by Shimamura and Okamoto et al. to obtain shock stand-off distance and shock wave angle in January 2019 [REF 2019]. HEK-X has been one of the expansion tubes being able to cover most severe heating environment of suborbital re-entry from Mars.

2.3 Other Expansion Tube Facilities

Expansion tubes are now routinely operated by a number of international research groups, besides the free-piston driven expansion tubes reviewed in section 2.2 of this thesis report: X2 and X3 in Brisbane [5]; HEK-X in Kakuda, Japan [9]; JX-1 in Sendai, Japan [11], there are a lot of expansion tubes driven by other kinds of drivers, for example, HYPULSE-SET in GASL [12]; JF16 at CAS [13]; HET at Caltech [14] and LENS-XX at CUBRC [15]. The investigation of other expansion tubes helps to find the real engineering relationship between dimension, cost and performance, which would provide significant guidance to the future design of X4.

2.3.1 Caltech HET

HET is a small-scale expansion tube facility designed by Dufrene, Sharma and Austin in 2006 and it is currently located at Hypersonics Group of Caltech [14]. A comprehensive design procedure for small-scale expansion tubes was presented by Dufrene et al. in 2007 [14].

The HET facility is constructed of honed 304/304L stainless steel (0.2 μm Ra inner surface finish) with the below specifications [14]:

- Driver: Diameter 152 mm; Length 1.22 m;
- Driven tube: Diameter 152; Length 3.96 m;
- Expansion tube: Diameter 152 mm; Length 3.96 m;
- Tube wall thickness: 0.95 cm;
- The primary diaphragm: typically, 0.159 cm thick 5052-H32 Al;
- Burst pressure of the primary diaphragm: 4300 ± 140 kPa;
- High enthalpy test conditions up to Mach 7.1;

The development process of this facility identified some practical limitations for developing an expansion tube such as diaphragm rupture timing and flow disturbance minimization which was a good guidance to create a functional design parameter space.

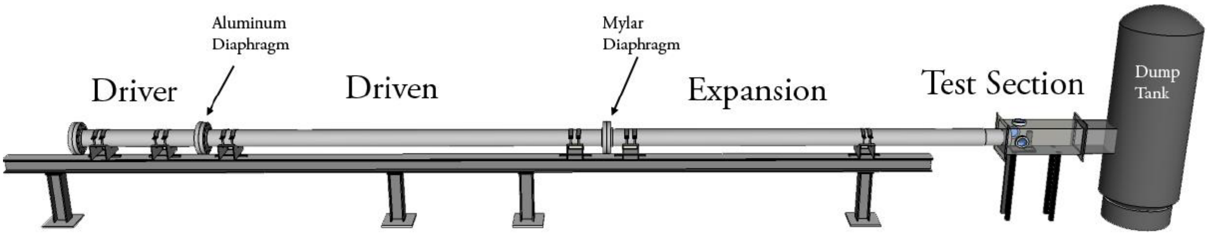


Figure 7. Engineering drawing of HET [16]

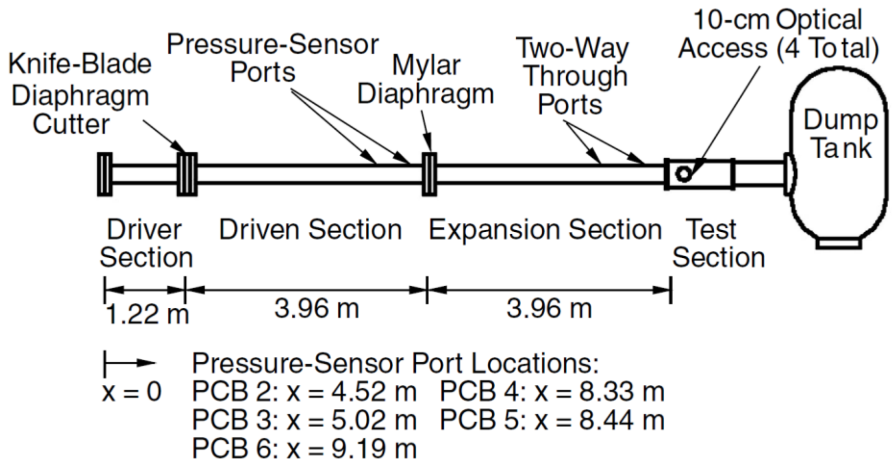


Figure 8. HET schematic diagram (taken from [14])

Dufrene's M. Sc. Thesis comprehensively presents the design process of the HET expansion tube, which is being kept in the format of a book in the library of University of Illinois, Urbana-Champaign.

2.3.2 JF16

JF16, another facility under the name of "JF series", is a shock-expansion tunnel located at Institute of Mechanics of Chinese Academy of Sciences in Beijing, China, which has a 6-meter long detonation driver. The main research purpose of this facility is to study physics and chemistry phoneme of hypervelocity flow especially high-temperature gas dynamics instead of targeting at scramjet testing and hypersonic planetary re-entry.

JF16 originally used a 60 mm × 60 mm section tube as the acceleration tube, which was optimised to a 68 mm diameter tube with newly developed 726 mm long nozzle commissioned (68 mm entry with 272 mm exit) in 2015 [17].

Experimental data showed that the test flow with a velocity of 10.2 km/s and a total enthalpy up to 45 MJ/kg can be generated successfully and with test duration up to 100 μs. The developed high-speed flow conditions provided fundamental and significant support for the physics and chemistry study of hypervelocity flow [13]. Figure 9 below is a schematic of JF16.

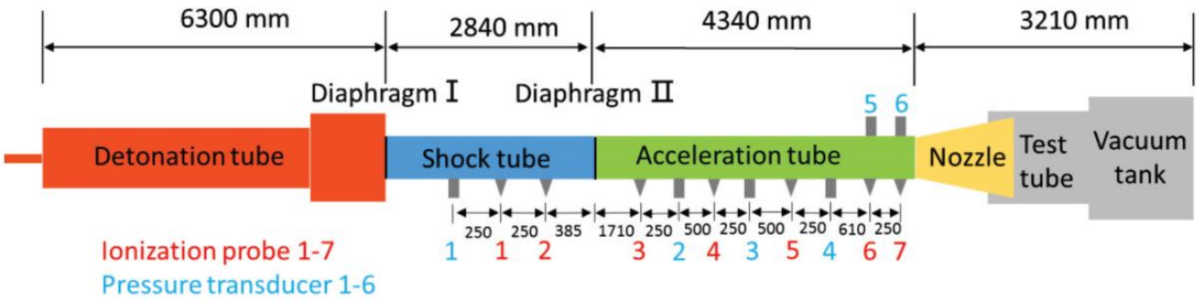


Figure 9. Schematic of JF16 (taken from [13])

- Driver: Diameter 105 mm; Length 6300 mm;
- Shock Tube: Diameter 68 mm; Length 2840 mm;
- Acceleration Tube: Diameter 68 mm; Length 4340 mm;
- Nozzle: Diameter, 68 mm entry with 272 mm exit; Length 726 mm.

2.3.3 HYPULSE

The HYPULSE facility is a dual-mode facility that can be configured in either Reflected Shock Tunnel (RST) or Shock Expansion Tunnel (SET) mode [18]. This facility is currently located at and operated by General Applied Science Laboratory (GASL Inc.) in Ronkonkoma, New York, USA [12].

Initially, when HYPULSE's pioneer facility at NASA Langley Research Centre was developed, it was considered to be driven by free-piston driver as an expansion tube. After the relocation of this facility, with the Helium and detonation driver finally commissioned, the Reflected Shock Tunnel mode of HYPULSE was developed in 1996. The realisation of HYPULSE mode transformation is achieved through the configuration of tubes, including removal of acceleration tube and length increase of shock tube from SET mode to RST mode.

Table 1 below summarises tube dimension sets of HYPULSE in varied Mach numbers for both modes, from which we can find the information that the length of shock tube is increased from RST mode to SET mode.

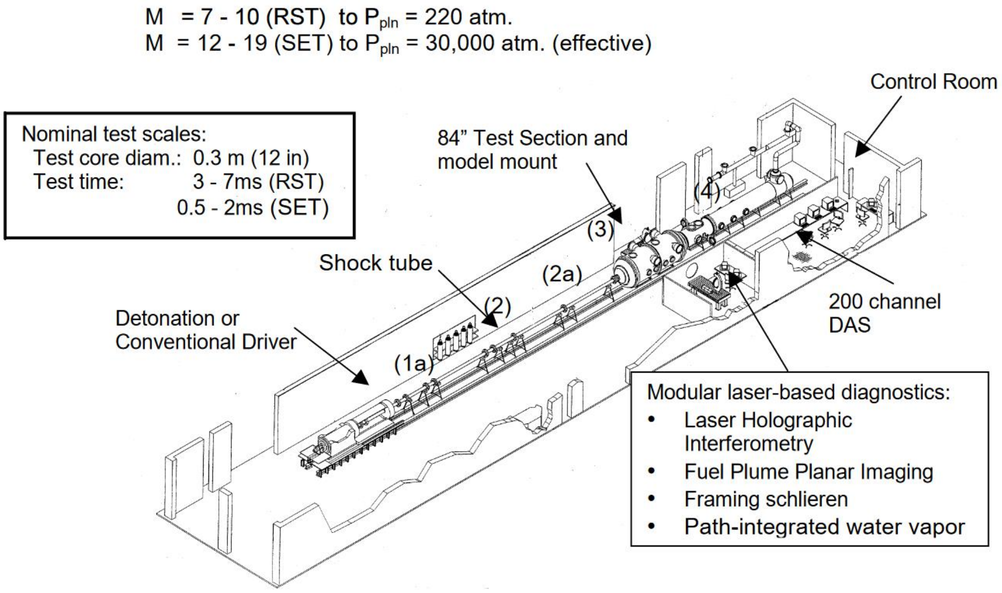


Figure 10. HYPULSE Facility (taken from [19])

Table 1. Dimension information of HYPULSE (data from [12, 18-20])

Flight Equivalent Enthalpy	**M7**	**M8-10**	**M15-21**
Mode	RST	RST	SET
Driver Length (Helium)(mm)	4880	2440	610
Driver Length (Detonation)(mm)	-	7680	7680
Shock Tude Diameter (mm)	152.4	152.4	152.4
Shock Tube (ST) Length (mm)	21870	16630	5090
Acceleration Tube (AT) Length (mm)	-	-	12630
Ratio of Length AT/ST	-	-	2.481

The most significant characteristic for HYPULSE is its wide range of simulated flight conditions (from Mach 5 to 25) which can be reached through transformation of the operation mode (the transformation normally costs one day labour) [REF].

The reported test time of HYPULSE is normally 3 – 7 ms (RST mode) and 0.5 – 2 ms (SET mode), which high-enthalpy flow conditions are achieved with sacrifice of test time. Figure 11 below is a diagram demonstrating the hypervelocity testing capability of HYPULSE.

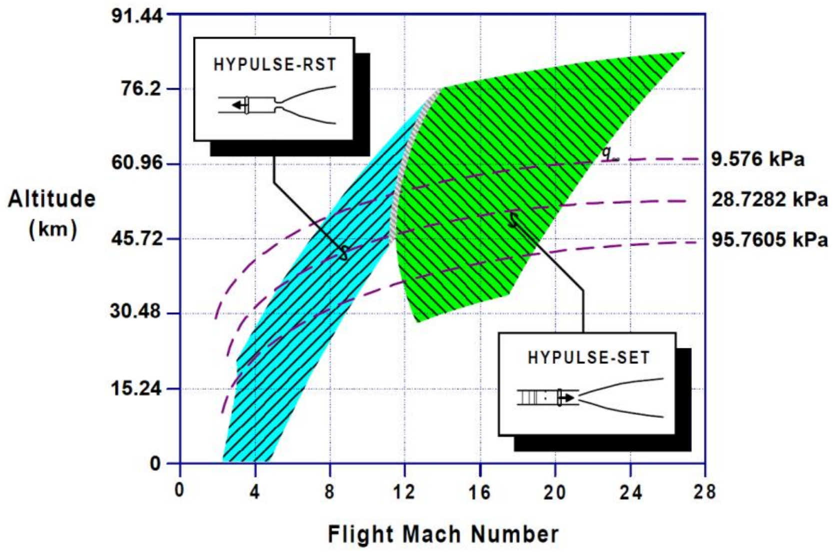


Figure 11. Simulation Capability of HYPULSE (adapted from [18])

HYPULSE-SET

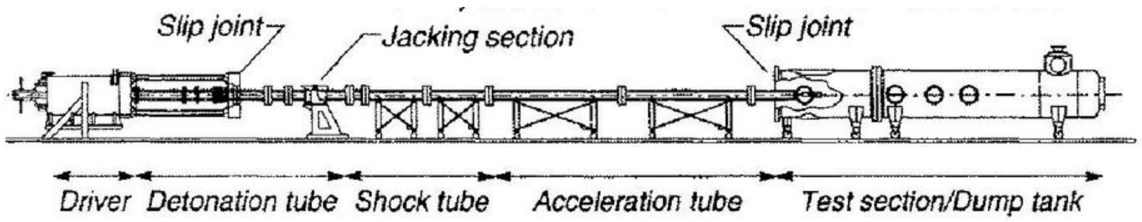


Figure 12. HYPULSE Facility in SET mode (MACH 12-25)(taken from[12])

HYPULSE-RST

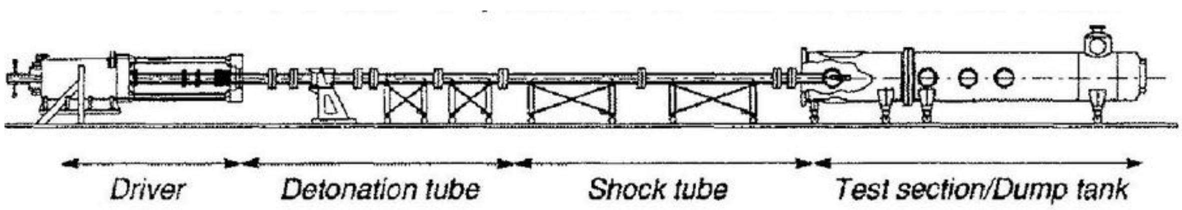


Figure 13. HYPULSE Facility in RST mode (MACH 5-10) (taken from [12])

Bigger test section of HYPULSE

The above Figure 13 and Figure 25 demonstrate a 4 feet diameter test section while the Figure 14 below shows a larger test section with 7 feet diameter reported by Chue et al. in 2002 [12].

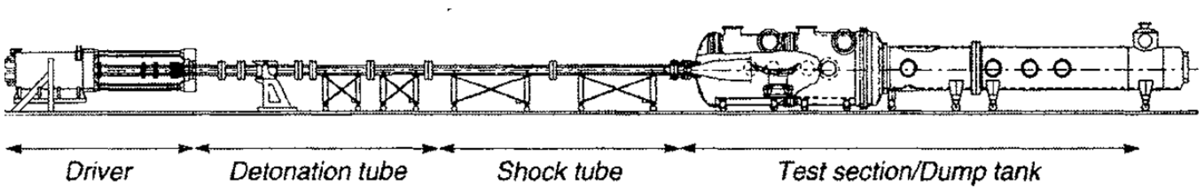


Figure 14. Larger test section of HYPULSE (taken from [12])

The bigger test section was developed to permit testing of larger models because of the addition of nozzles. The test section upgrade was done as the development of RST mode and nozzles went on [20].

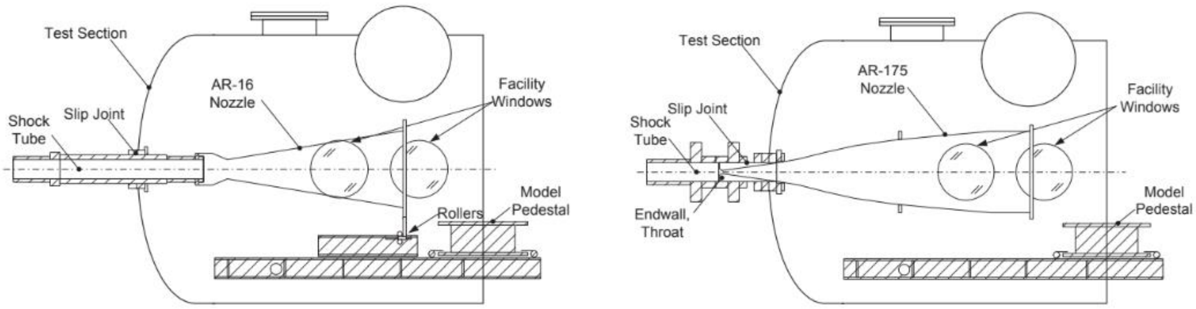


Figure 15. Schematic of nozzle configuration (AR-16 and AR-175) in HYPULSE test section (taken from [20])

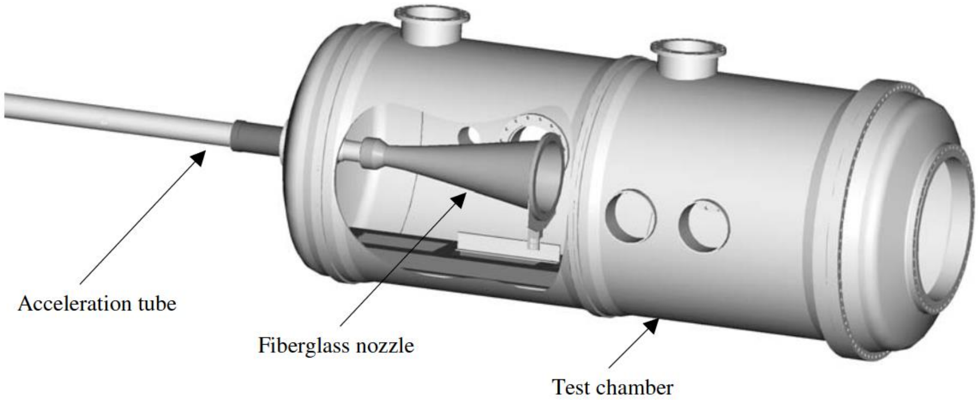


Figure 16. An engineering drawing to demonstrate the HYPULSE nozzle and its installation (taken from [20])

Figure 15 is a schematic of nozzle configuration in HYPULSE test section while the left side gives the AR-16 nozzle configuration of SET mode and the right side gives the AR-175 nozzle configuration of RST mode [20]. Table 2 below summarises the nozzle information of HYPULSE.

Table 2. HYPULSE nozzle information

Flight Equivalent Enthalpy	**M7**	**M8-10**	**M15-21**
Mode	RST	RST	SET
Nozzle Throat Diameter (mm)	50.8/44.4	50.8/44.4	152.4
Nozzle Length (mm)	2640	2640	1550
Nozzle Area Ratio	175/225	175/225	16

For particular details of developed operating conditions of HYPULSE, please refer to Appendix.

HYPULSE, as an intermediate sized facility (total length around 40 meters), has extreme stagnation pressure and enthalpy without significant flow contamination at Mach 12 to 25 operating in SET mode. HYPULSE was targeting at supporting hypersonic scramjet research for the NASP and Hyper-X programs, which might be differed from the target of X4 – aiming at planetary entry research. However, the engineering experiences of tunnel configuration mode from HYPULSE are significantly useful for the further development of new expansion tube facilities.

2.3.4 HXT of TEXAS A&M

This facility is a large-scale Hypervelocity Expansion Tunnel (HXT) located at Texas A&M University that provides total enthalpies up to 30 MJ/kg.

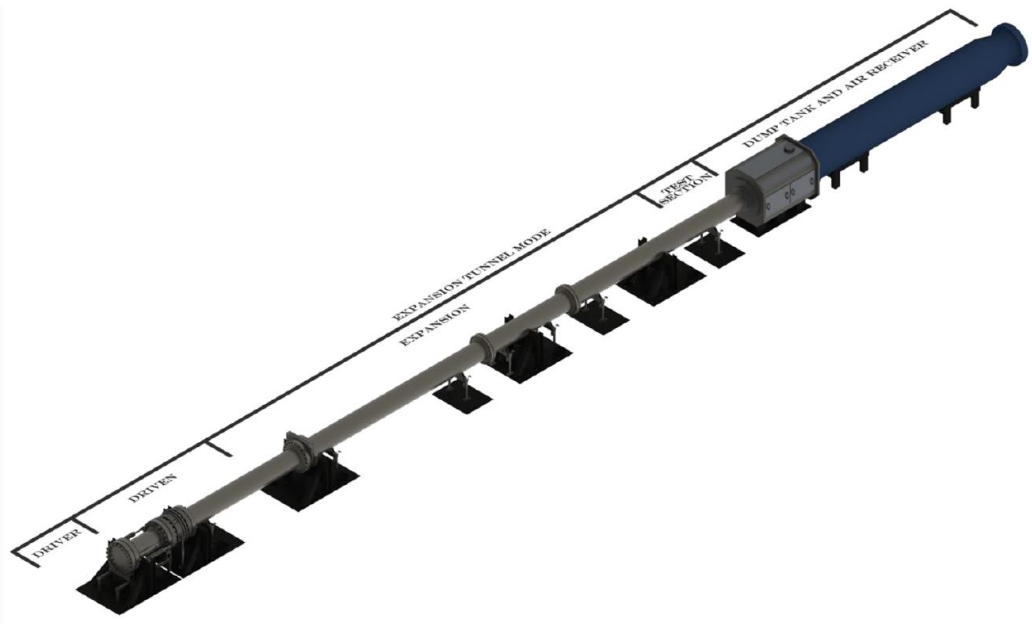


Figure 17. Engineering Drawing of HXT (taken from [21])

The following table summarises important dimension information of HXT:

Table 3. HXT Dimension Information

Facility	HXT
Location	Texas A&M, USA
Type	Expansion Tube
Driver	Helium
Length of Compression Tube (L_CT, m)	Helium Driver 1 ~ 1.7
Diameter of Driver Tube (D_CT, mm)	Helium Driver 500
L_CT/D_CT	2 ~ 3.4
Length of Shock Tube (L_ST, m)	4.6
Diameter of Shock Tube (D_ST, mm)	**500**
Acceleration Tube Length (L_AT) m	15.2
Acceleration Tube Diameter (D_AT) mm	**500**
TL (Total Length, m)	30
h0 (Total enthalpy, MJ/kg)	5 - 11

HXT's structure permits the use of acceleration and shock tube with very large diameter.

2.4 Free-piston Shock Tunnels

Free-piston shock tunnels have a similar overall structure and driver design process with free-piston expansion tubes. Adding an acceleration tube to a shock tunnel with related tube configurations has been a common technique to configure a shock tunnel to an expansion tube.

Investigation into free-piston shock tunnels could help to understand the free-piston driver design theories and how the theories were applied to facility development.

2.4.1 T4 Shock Tunnel

After Professor Stalker's pioneer research of shock tunnel theories and genius invention of free-piston driver, the T-series facilities were developed and the initial T1, T2 and T3 were built at the Australian National University. In 1987, Professor Stalker and Professor Morgan [22] developed the T4 shock tunnel at The University of Queensland as the 4th facility of T-series shock tunnel.

T4 shock tunnel was developed with an important objective – producing test flows suitable for scramjet testing, which is different from the objective of proposal X4 (planetary re-entry research directed). It was reported by Professor D. Mee et al. in 2015 [23] that a large proportion of shots in T4 have been aiming to research into scramjets and related subsystems. Latest reports and papers about T4 are mainly talking about the following research fields:

- Measurement of Forces on Scramjets;

- Skin-Friction Reduction by Boundary Layer Combustion;

Figure 18 below is a schematic of T4 shock tunnel.

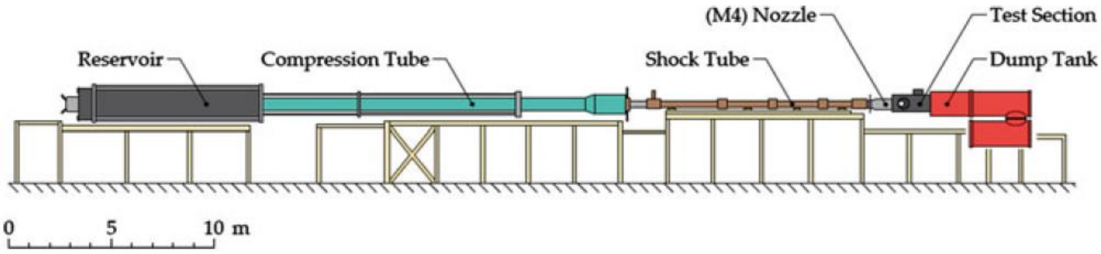


Figure 18. Schematic of T4 Shock Tunnel

- Compression tube: Length 26 m; Bore 229 mm;
- Shock tube: Length 10 m; Bore 76 mm;
- Nozzle exit diameter: 135, 263, 270, 273, 375 mm;
- Test time: 1.5 ms at 7.6 MJ/kg condition (nozzle-supply enthalpy);

2.4.2 T5 Shock Tunnel

In 1990, T5 shock tunnel began to be operational at GAL (Graduate Aerospace Laboratories) of Caltech (California Institute of Technology). Figure 19 is a schematic of the T5 facility with enlargements of the important components reported by H. G. Hornung et al. in 2015 [23].

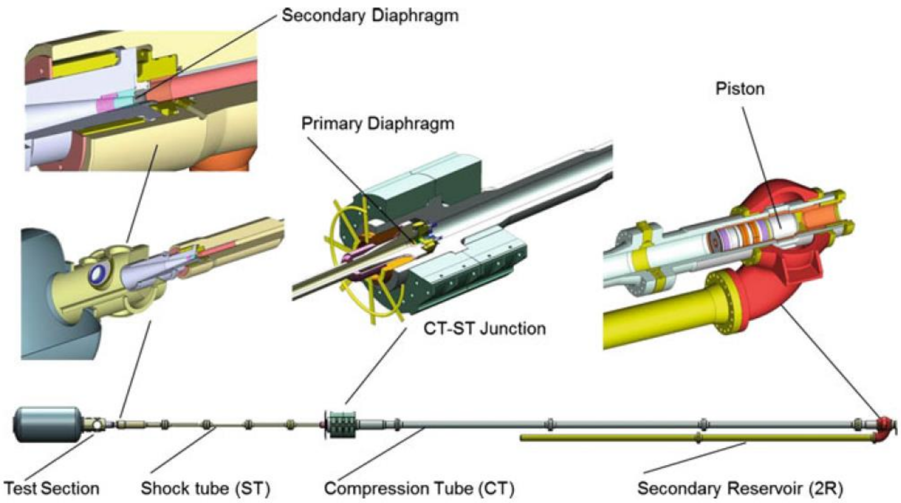


Figure 19. Schematic of the T5 facility with enlargements of the important components (taken from [23])

The specifications of T5 are:

- Compression tube: Length 30 m; Diameter 300 mm;

- Shock tube: Length 12 m; Diameter 90 mm;
- Total enthalpy: 20 MJ/kg;
- Total pressure: 100 MPa;
- Test time: 1 ~ 2 ms;
- Piston mass: 120kg;
- Inertial mass:14 t.

T5 is extensively used in the following research fields [23]:

- Enthalpy Effects on Hypervelocity Boundary Layer Transition and Passive Control of Transition;
- Influence of Non-equilibrium Dissociation on the Flow Produced by Shock Impingement on a Blunt Body;
- Gas Dynamical Detection of Driver Gas Contamination.

2.4.3 T6

T6 facility was built at the University of Oxford with coupling of the previous T3 free-piston driver at Australian National University and barrels, nozzles and test section of the Oxford gun tunnel. Three operation modes have been developed for T6:

- Reflected Shock Tunnel mode;
- Expansion Tube mode;
- Shock Tube mode.

Figure 20 below is a demonstration of T6 facility in the form of CAD drawing.

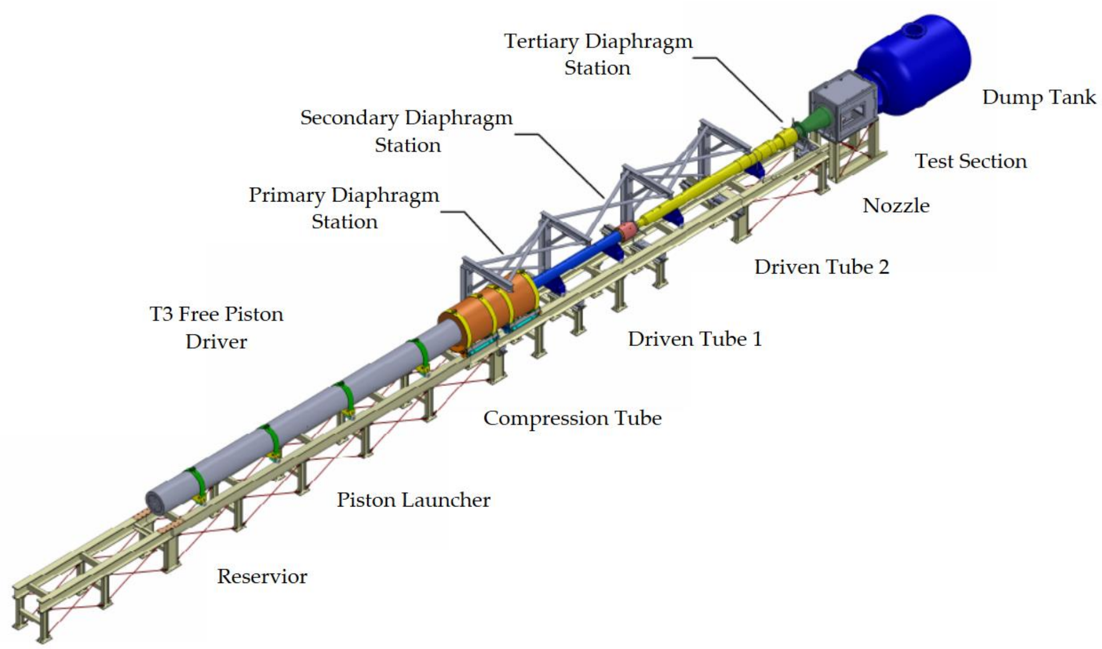


Figure 20. Engineering drawing of T6 in RST mode (taken from [24])

T6 has 2 driven tubes and 1 extension tube (same dimension to driven tube 1) to configure its operation mode. Selected specifications of T6 are summarised below in dot points:

- Driver: Length 6 m; Diameter 300 mm;
- Driven tube 1: 1.75 m; Diameter 96.3 mm;
- Driven tube 2: 4.24 m; Diameter 96.3 mm;

The three operation modes of T6 permit its wide range of testing capability:

- Scramjet testing: Flow speeds from 2 to 6 km/s in RST mode;
- Re-entry: Flow speeds over 6 km/s in expansion tube mode;
- Shock layer radiation experiments: Flow speeds above 4 km/s in shock tube mode.

The RST mode of T6 has a maximum speed capability (approximately 6.5 km/s for air) which fulfils air-breathing engine tests and sub-orbital aero-thermodynamics research. When T6 operating in expansion tube mode, it has a similar dimension and performance to the X2 at UQ, which would be able to generate earth re-entry flow conditions. Furthermore, shock tube mode of T6 aims to undertake shock layer radiation experiments [24].

T6 is a multi-mode facility with the capability to produce a wide range of flow conditions for various hypersonic research fields.

2.4.4 HIEST

HIEST is a large-scale high enthalpy shock tunnel located at the JAXA Kakuda Space Center Japan, which was designed to accomplish the driver tuned operation throughout the requirements for the H-II Orbiting Plane aerothermodynamics and the scramjet tests. HEK shock tunnel, which was configured to HEK-X expansion tube, was the pilot facility for the development and technical verification of HIEST. The following dot-points summarise main specifications of HIEST:

- Compression tube: Length 42 m; Diameter 600 mm;
- Shock tube: Length 17 m; Diameter 180 mm;
- Piston mass: 220, 290, 440, 580, 780 kg;
- Maximum stagnation enthalpy: 25 MJ/kg;
- Test time: over 2 ms;

HIEST, as one of the facilities of testing ability in Japan, has been used for a wide range of research activities, some of which were summarised below [23]:

- Development of Force Measurement Technique and Investigation of Real-Gas Effect on Aerodynamic Characteristics;
- Investigation of High-Enthalpy Heat Flux Augmentation;
- Investigation of Hypersonic Boundary Layer Transition;
- Etc...

2.4.5 HEG

The HEG is a free piston driven shock tunnel commissioned in 1991 at Göttingen, Germany. Figure 21 below is a schematic of HEG shock tunnel.

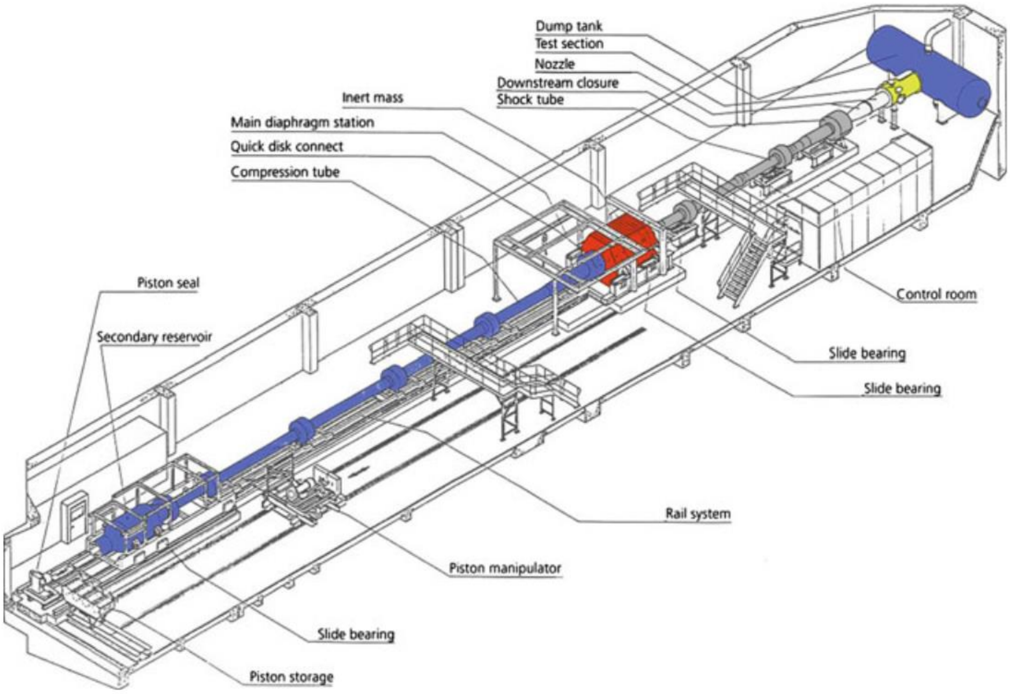


Figure 21. Schematic of the HEG High Enthalpy Shock Tunnel at DLR Göttingen, Germany (taken from[23])

- Total length: 62 m;
- Total weight: 280 t;
- Stagnation enthalpies: up to 23 MJ/kg;

HEG was originally designed for the investigation of high temperature effects such as thermal and chemical relaxation on the aerothermodynamics of entry or re-entry space vehicles, after years of operation, the research fields have been extended but not limited to [23]:

- High Enthalpy Cylinder Shock Layer Investigations;
- Free Jet Testing and Numerical Analysis of Scramjet Flow Paths;
- Laminar to Turbulent Hypersonic Boundary Layer Transition Characterization and Passive Control；
- Study of hypersonic flow at Ma 8 und Ma 10 in 20km up to 40 km altitude

2.4.6 HELM

HELM is located at Faculty of Aerospace Sciences, Institute for Thermodynamics, University of the Federal Armed Forces München commissioned in 2010. This very young facility has a highlighted unique design philosophy - its capability to easily vary the tube length to develop new operation conditions.

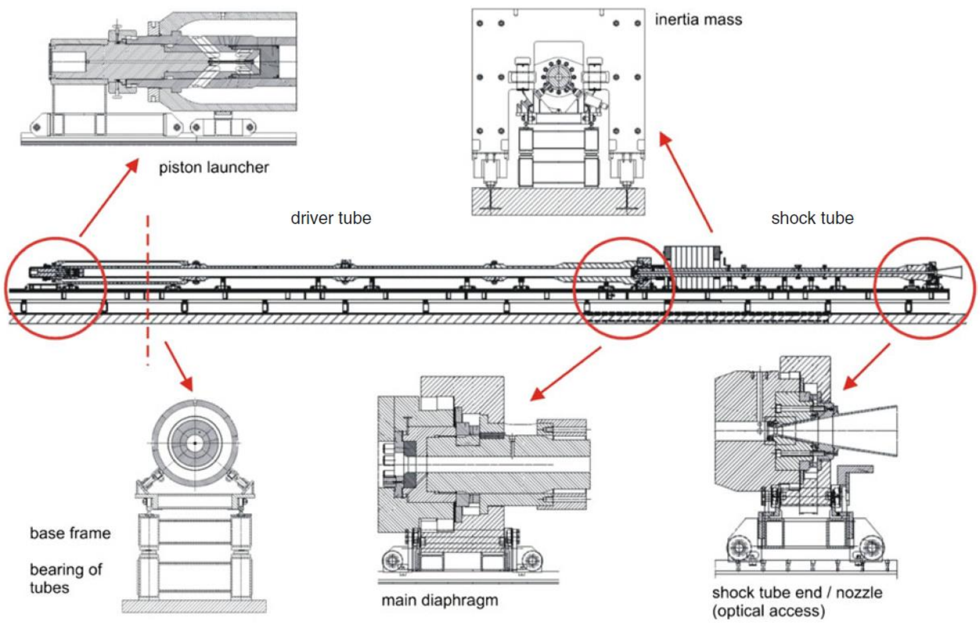


Figure 22. Demonstration of HELM shock tunnel (taken from [25])

The HELM is designed to be able to vary the driver and the shock-tube length easily, which is achieved by a modular design and tubes are installed on moveable connections.

Table 4. Information of HELM Facility

Facility	HELM
Location	UAFM, Germany
Type	Shock Tunnel
Driver	Free-piston
L (Length of CT, m)	21
D (Diameter of CT, mm)	286
CT L/D	73
L_ST(Length of ST, m)	8,9,10,11
D_ST (Diameter of ST, mm)	95
L_ST/D_ST	84,95,105,116
L_CT/L_ST	2.625, 2.33, 2.1, 1.9
D_CT/D_ST	3.011
Nozzle exit diameter (mm)	3.011
h0 (Total enthalpy, MJ/kg)	20-25
P0 (Total pressure, MPa)	100

2.4.7 FD21

FD-21 is a large-scale free-piston driven shock tunnel commissioned in 2016 and constructed by China Academy of Aerospace Aerodynamics (CAAA) to meet the needs for deep space exploration and other hypersonic research. CAAA was established by Prof. H. S. Tsien who would be the first researcher to deliver the idea of hypersonic in his pubulication "*Similarity Laws of Hypersonic Flows*" in April 1946 [26].

Manufacuring huge shock tunnel facility is extremely challenging. In order to bear the load from heavey piston launch, FD21 is built above a 142-meter high-presion rail system with fine milling surface finish (Ra 3.2) to permit its floating tunnel structure which lets the main body (600 t) slide along axisle direction after each shot. It was measured that the height error is less than 0.5 mm along the 140-meter rail. The calculation indicates that a maximum 100-mm axis displacement happens for a 600-tonne body after a shot .

One of other hard points is the facility-wide straightness especially within compression tube. The compression tube and shock tube are divided into several sub-section tubes (12 sub-sections for compressin tube and 24 sub-sections for shock tube). Each sub-section of compression tube was manufactured and processed by large-scale boring and grinding machines to achieve a honed finish (Ra 0.8) and high-precision section-alignment. The engineering experiences from massive construction of infrastructures in China helped this large-scale manufacturing accomplished. When assemling these sub-sections together, the overall facility axis alignment precision is significant to be controlled as a minor exceeding of accumelated assembly errors of inner surface alignment would cause severe diaseter after the launch of a heavy piston. Besides the challenge of overall-facility precision, the sealing between sub-sections is vital as well or the tube vacuum degree (design requirement is 5 Pa) would be insuifficient to develop desired flow conditions.

Figure 23 below is a schematic to demosntrate the overall structure of FD-21 and the following dot-points summerise some parametes of this huge facility.

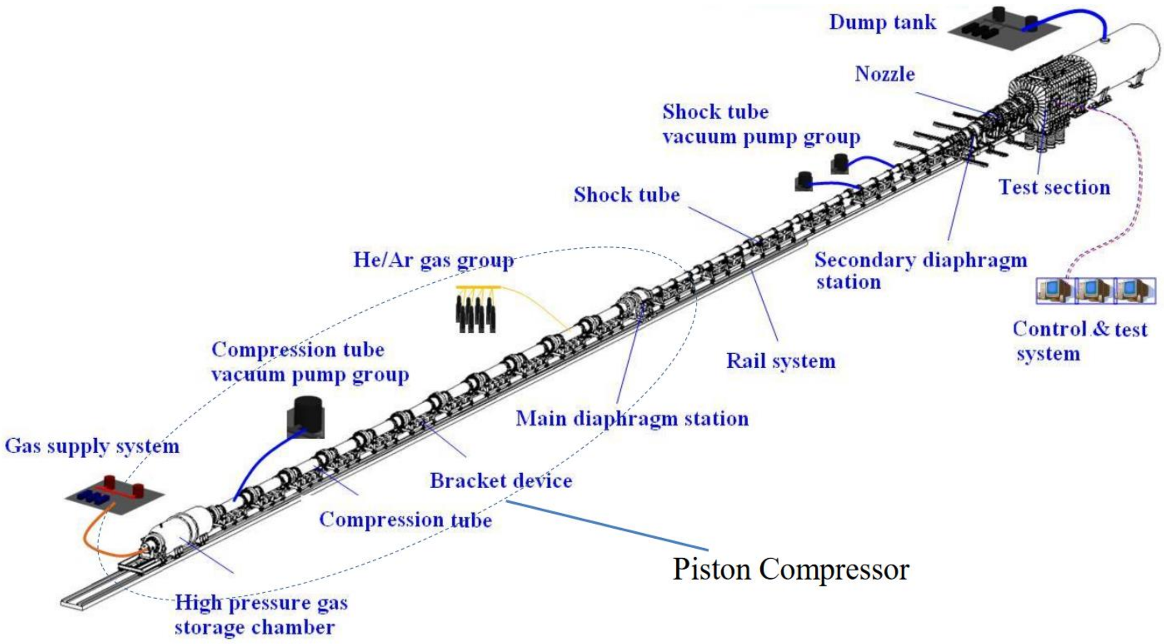


Figure 23. Schematic of the FD – 21 free-piston shock tunnel (taken from [27])

Partial specifications of FD21 are summarised below:

- Total length: 170 m;
- Total mass: 600 t;
- Compression tube: Length 75 m; Bore 668 mm; Design maximum pressure 70 MPa;
- Shock tube: Length 36 m: Bore 290 mm; Design maximum pressure 100 MPa;
- Nozzle: Entry diameter 1.2 m; Exit diameter 2 m;
- Test section: Volume 230 m^3; Design pressure 20 MPa;
- Piston mass: 120 kg, 200kg, 300kg and 600 kg;
- Reservoir: Volume 24 m^3; Normal operation pressure under 20 MPa.

FD-21 is currently the largest free-piston shock tunnel around the world. The 2-meter exit diameter nozzle and following huge test section permit test of large models while the 75-meter long compression tube can provide a relatively longer constant pressure after the primary diaphragm rupture. This large facility has developed varied flow conditions (e.g. Mach 10, 15 18 with 2 ~ 5 ms test time in 2018) after the reported facility calibration in 2017.

2.5 Other Shock Tunnels

2.5.1 JF12

JF12 is an extraordinarily large-scale shock tunnel driven by detonation driver located at Beijing and developed by Institute of Mechanics of Chinese Academy of Sciences. JF12 targets at long-time scramjet testing (over 100ms), which was achieved through the main reasons: its large scale and tailored-interface operation.

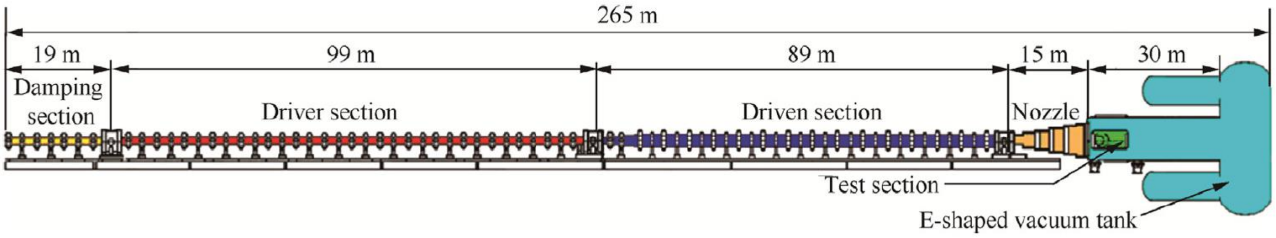


Figure 24. Schematic of JF12 detonation-driven shock tunnel (taken from [28])

- Expenditure: 46 Million Chinese RMB (10 Million AUD equivalent)
- Construction: Began in 2008 and finished in 2012;
- Total length: 265 meters;
- Detonation Driver: Length 99 m; Bore 400 mm;
- Shock tube: Length 89 m; Bore 720 mm.

The main characteristics of JF12 comparing other shock tunnels are:

- Very long test time (over 100 ms);
- Being able to "reproduce" the desired flow conditions rather than "simulate";
- Large test section.

JF12 was designed to target at scramjet testing, for example, one of its developed flow conditions is Mach number 7.0 at 35 km altitude with total enthalpy 2.5 MJ/kg. It has the capability of reproducing uncontaminated airflows with Mach numbers 5 - 9 at altitude of 25–50 km.

The experiences of JF12 indicate that a large facility would be extremely useful to advance the pace of hypersonic research, however the related construction cost and operation cost are exceedingly heavy. Without national level grant, facilities of such extraordinary scale would not be operational.

2.5.2 JF22

According to the media release of Chinese Academy of Sciences, a new hypervelocity impulse facility possibly named JF22 is under construction funded by National Natural Science Foundation of China (NSFC) [29]. Some released information for JF22 is summarised below:

- Funder: National Natural Science Foundation of China (NSFC);
- Institute: Institute of Mechanics, Chinese Academy of Sciences;

- Expenditure: 77.102 million Chinese RMB (almost 16 million AUD equivalent);
- Location: Beijing, China;
- Driver: detonation.

2.5.3 LENS-series Facilities

"LENS" means Large Energy National Shock tunnels, which is used to name the series of hypersonic impulse facilities of Calspan-University of Buffalo Research Center (CUBRC) in New York, USA. The LENS series facilities within CUBRC are listed below:

- LENS – I Shock Tunnel
- LENS – II Shock Tunnel
- LENS – X Expansion Tunnel
- LENS – XX Expansion Tunnel

The following Table 5 summarises the specifications and performance of LENS facilities.

Table 5. The specifications of LENS facilities [15]

	LENS - I	LENS - II	LENS - X	LENS - XX
Mode	Shock Tunnel	Shock Tunnel	Expansion Tunnel	Expansion Tunnel
Driver	Heated Light Gas	Light Gas	Light Gas	Heated Light Gas
Total Enthalpy (MJ/kg)	-	-	22.5	90 - 120
Total Temperature (K)	6300	2500	-	-
Total Pressure (MPa)	150	26	-	-
Simulated Altitude (km)	7 - 92	0 - 62	35 - 73	20 -75
Simulated Velocity (m/s)	900 - 4500	700 - 2700	4267 - 6700	up to 13000
Mach Number	6 - 22	3 - 15	14 - 22	5 - 30
Test Time (ms)	25	100	4	4

Currently, the largest expansion tube in the world is the Lens-XX which has the capacity to measure heat transfer in flows ranging from 3-8.4 km/s at enthalpies from 5-36 MJ/kg to simulate re-entry into Earth and entry into other planetary atmospheres.

2.6 Summary and Comparison

This section summarises the investigation results in the form of tables.

2.6.1 Free-piston Expansion Tunnels

Table 6. Summary of Free-piston Expansion Tunnels

	X2	**X3**	**HEK-X**	**JX-1**
Location	UQ, Australia	UQ, Australia	Kakuda, Japan	JAXA, Japan
Length of Compression Tube (L_CT, m)	3.8	14	16	3
Diameter of Compression Tube (D_CT, mm)	256.8	500	210	150
L_CT/D_CT	14.8	50	76.19	20
Length of Shock Tube (L_ST,m)	3.424	12	6.5	1.8
Diameter of Shock Tube (D_ST, mm)	85	200,180	72	50
L_ST/D_ST	40.28	50, 66.67	90.3	36
D_CT/D_ST	3.02	2.5, 2.7	2.92	3
Acceleration Tube Length (L_AT) m	5.155	25	9.4	3.6
Acceleration Tube Diameter (D_AT) mm	85	180	72	50
L_AT/D_AT	60.65	138.89	130.56	72
L_CT/L_ST	1.11	0.64, 1.4, 2	2.46	1.67
L_AT/L_ST	1.51	2.08	1.45	2
TL (Total Length, m)	23	67	35	13.6
h0 (Total enthalpy, MJ/kg)	30	30	25	40

2.6.2 Other Expansion Tunnels

Table 7. Expansion Tunnels (Not driven by Free-piston driver)

	HYPULSE - SET	**HET**	**HXT**	**JF16**
Location	GASL, USA	Caltech, USA	Texas A&M, USA	CAS, China
Driver	Helium Detonation	Helium	Helium	Detonation
Length of Driver Tube (L_Driver, m)	Helium Driver 0.61 Detonation Driver 7.68	Helium Driver 1.22	Helium Driver 1 ~ 1.7	Detonation Driver 6.3
Diameter of Driver (D_Driver, mm)	152.4	Helium Driver 152	Helium Driver 500	Detonation Driver 105
L_Driver/D_Driver	50.4	8.03	2 ~ 3.4	60
Length of Shock Tube (L_ST,m)	5.09	3.96	4.6	2.84
Diameter of Shock Tube (D_ST, mm)	152.4	152	500	69
Acceleration Tube Length (L_AT) m	12.63	3.96	15.2	4.34
Acceleration Tube Diameter (D_AT) mm	152.4	152	500	68
L_AT/L_ST	2.48	1	3.30	1.52
TL (Total Length, m)	40	15	30	16.69
h0 (Total enthalpy, MJ/kg)	30	14	5 - 11	20 - 25

2.6.3 Free-piston Shock Tunnels

Table 8. Summary of Free-piston Shock Tunnels

	T4	**T5**	**T6**	**FD21**	**HEG**	**HELM**	**HIEST**
Location	UQ, Australia	Caltech, USA	Oxford Uni, UK	CAAA, China	DLR, Germany	UAFM, Germany	JAXA, Japan
L (Length of CT, m)	26	30	6	75	33	21	42
D (Diameter of CT, mm)	229	300	300	668	550	286	600
CT L/D	113	100	200	112	60	73	70
L_ST(Length of ST, m)	10	12	6	35	17	8,9,10,11	17
D_ST (Diameter of ST, mm)	76	90	96.3	290	150	95	180
L_ST/D_ST	132	133.33	62.31	120	113	84,95,105, 116	94
L_CT/L_ST	2.6	2.5	1	2.143	1.941	2.625, 2.33, 2.1, 1.9	2.471
D_CT/D_ST	3.013	3.333	3.115	2.303	3.667	3.011	3.333

Chapter 3 Review of Design Methodology

3.1 Driver Piston Design

For expansion tube driven by free-piston driver, the piston is the core part for the driver. This chapter mainly talks about the important theories to design a driver piston for X4.

The following first section 3.1.1 talks the details of driver tuned operation. In 2011, Professor Morgan and Gildfind, D.E. *et al* indicated the importance of achieving "Tuned" operation of piston for driver optimisation [8]. At UQ, after 2009, "Tuned" piston was applied to generate scramjet test flows in X series expansion tubes to optimise the piston mass as the relative length of compression tube limited further development of flow conditions during then.

With X4's requirement of only targeting high enthalpy planetary entry flows, the idea of tuning its driver is to significantly reduce the length of compression tube within lab space availability with a relatively lighter piston (because ideally it would be better to have a very long compression tube to develop desired theoretical operation condition [30]).

Meanwhile, with a shorter compression tube and lighter piston, the overall facility construction cost can be brought down dramatically as the manufacturing of piston and compression tube (including inertia mass) contributes the largest portion of overall facility cost [31].

3.1.1 Driver Piston Tuned Operation

The importance of achieving 'tuned' operation of the free-piston driver was highlighted by Professor Stalker in 1967 [32]. Normally, a tuned free-piston driver can be achieved through manipulating the following variables of an expansion tube:

- Driver gas properties including driver fill pressure ($p_{A,0}$) and compression ratio (λ) etc…;
- Compression tube Length and Diameter;
- The available reservoir pressure and volume.

Case study:

Tuned operation was applied on X2 and X3's new lightweight driver piston commissioning to develop scramjet access-to-space flow conditions between Mach 10 – 15. X2 requires "tuned operation" involving high piston speed (> 200 m/s) to achieve desired flow conditions for scramjet testing, which pushed the development of a lightweight 10.5 kg piston in 2010 by Gildfind and Professor Morgan et al. in 2010 [8] to replace the original 35 kg piston by Scott in 2006 [7]. X3's new 100.8 kg piston commissioned (designed by D. E. Gildfind and Professor Morgan et al. in 2015 [33]) to replace its original 200 kg piston.

The reason why X2 and X3 needed new tuned lightweight piston is because the previous free-piston drivers of X2 and X3 before tuned operation used relatively heavy pistons and short compression tubes. However, for a slower-speed piston, the driver gas slug is assumed to be approximately constant on volume at the end of its stroke when compared to the time scales of test flow generation. After rupture, a rapid pressure drop was caused by the unsteady expansion in the driver gas, which might interfere with downstream flow processes before or during the test time by a strong downstream u+a wave [8].

Before the commissioning of the light weight pistons for X2 and X3, some hypervelocity test flow conditions (for example, planetary re-entry velocity from 6 to 10 km/s) had been used in UQ expansion tubes. However, under these conditions, driver gas was maintained at high pressure for a relatively short duration because of the disadvantages of a relatively short compression tube talked in the above chapter introduction paragraph. Developing scramjet test flow conditions requires a much longer duration to let the driver pressure maintain at target level, which led to the application of piston drive tuned operation [8].

Section conclusion:

The most important requirement of designing X4 is that it will target high enthalpy planetary entry flows instead of targeting the scramjet experiments. Thus, tuned operation experiences on X2 and X3's scramjet flow conditions development might not be significantly guiding the preliminary design procedure of X4 as this operation was used to conquer the limitation of their insufficient driver length. However, it is necessary to be considered for the initial compression tube design of X4 as the idea of tuning its driver is to significantly reduce the length of compression tube with a relatively lighter piston. Shorter compression tube with lighter piston can dramatically decrease the facility overall cost if the predicted performance fulfils the design requirements.

3.1.2 Stalker Analysis

The free-piston driver methodology developed by Professor Stalker [32] can help to determine the necessary piston mass if the compression tube dimension and some related driver gas parameters are given.

Some parameters used for Stalker Analysis are given in the Nomenclature section and demonstrated in Figure 25:

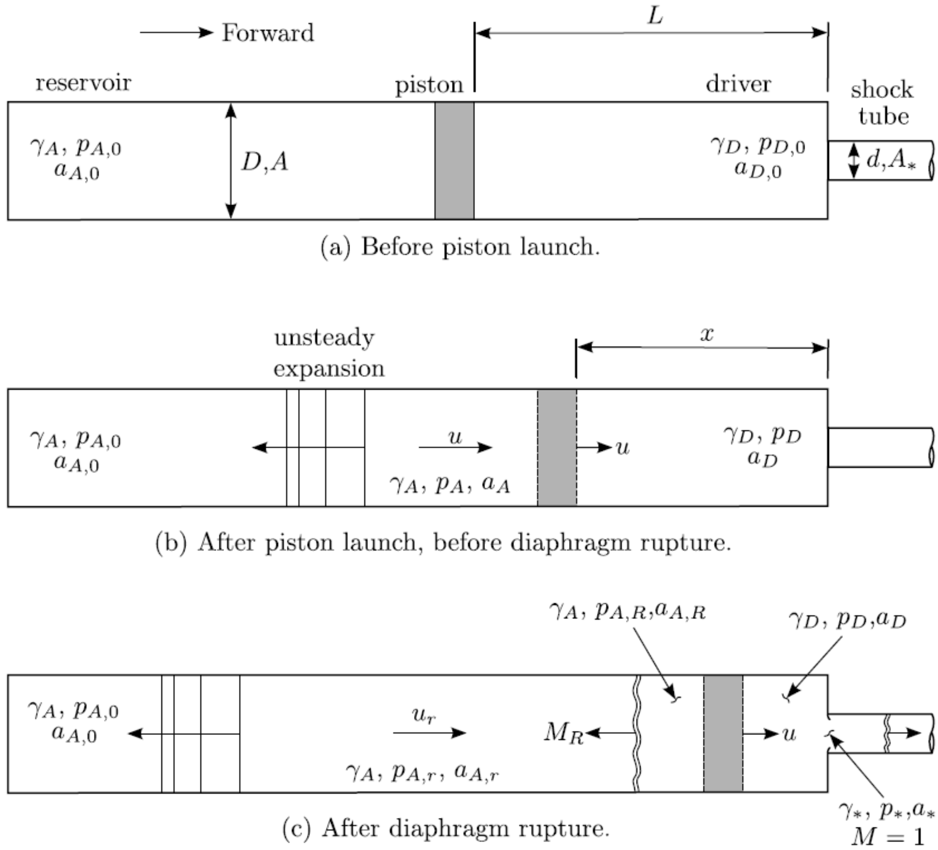


Figure 25. Schematic diagram of free-piston driver with analytical parameters defined (taken from [34])

In front of the piston in Figure 8, it is driver gas with driver gas parameters subscripted by letter "D". The gas behind the piston is supplied by reservoir with reservoir gas parameters subscripted by letter "A".

For the moment following primary diaphragm rupture, the driver gas density reaches maximum. This moment is defined to be condition "*r*" with time $t = 0$ set at this time. With the assumption of constant reservoir and driver pressure after the launch of piston, Professor Stalker finally reached the following set of equations to reflect a non-dimensional relationship between driver gas density and time:

$$\frac{\rho_D}{\rho_{D,r}} = \frac{1}{1 - z + \frac{k}{2}z^2} \cdot exp\left[\frac{-2}{\sqrt{2k-1}} \cdot \left(tan^{-1}\frac{kz-1}{\sqrt{2k-1}}\right) - tan^{-1}\frac{-1}{\sqrt{2k-1}}\right] \quad (1)$$

$$z = \frac{U_r}{x_r} \cdot t \quad (2)$$

$$\frac{x}{x_r} = \frac{k}{2} \cdot z^2 - z + 1 \quad (3)$$

$$\frac{u}{U_r} = 1 - k \cdot z \quad (4)$$

$$Condition\ r: \frac{d\rho_D}{dt} = 0, (u)_r = U_r = -\left(\frac{dx}{dt}\right)_r$$

The parameter k is the original factor (0.5) of kinetic energy equation although Professor Stalker nominated $k = 1$ to marginate safety. With the following assumed parameters:

- Driver gas Ratio of Specific Heats: $\gamma_D = \frac{5}{3}$
- $k = 1$
- Reservoir gas expands to piston back by an unsteady expansion

The diagram can be plotted to illustrate the non-dimensional driver gas density change as z varies, which is the following Figure 26 plotted by Python Matplotlib.

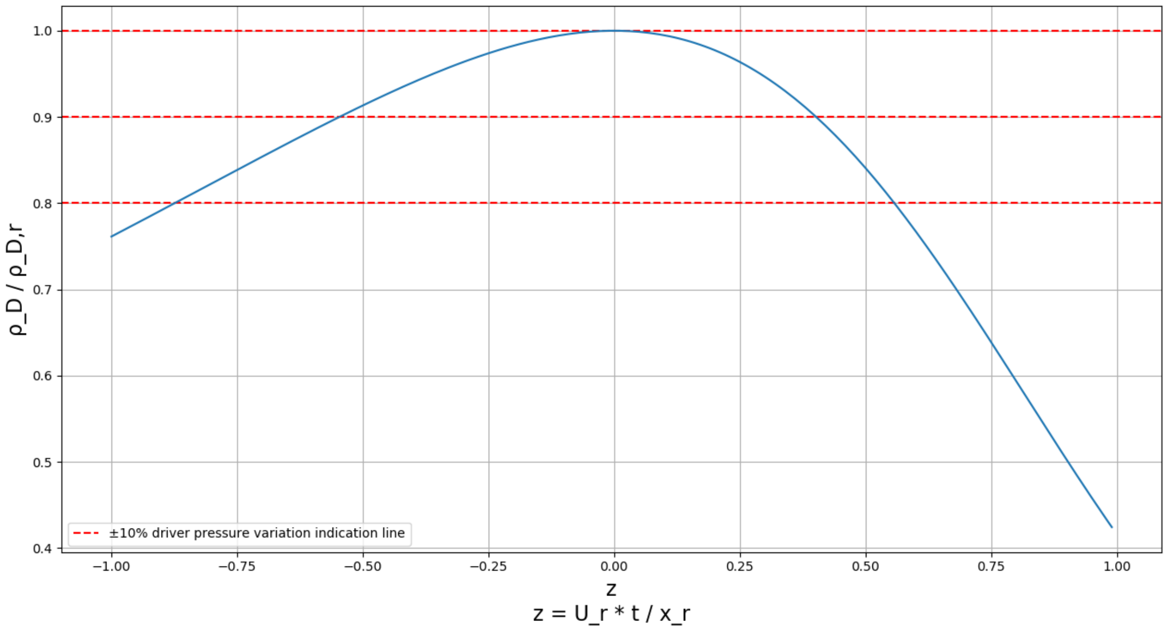


Figure 26. Variation of non-dimensional driver gas density using Stalker Analysis

UQ researcher Gildfind in 2012 [34] used a ±10% driver pressure variation to determine z values from the inspiration of driver piston over-driving theory (summarised in Appendix) by Itoh et al. in 1998 [35]. The ±10% driver pressure variation analysis aims to optimise the primary diaphragm rupture timing and increase the duration of driver gas supply, which is demonstrated in the following Figure 27 created by Gildfind in 2012 [34].

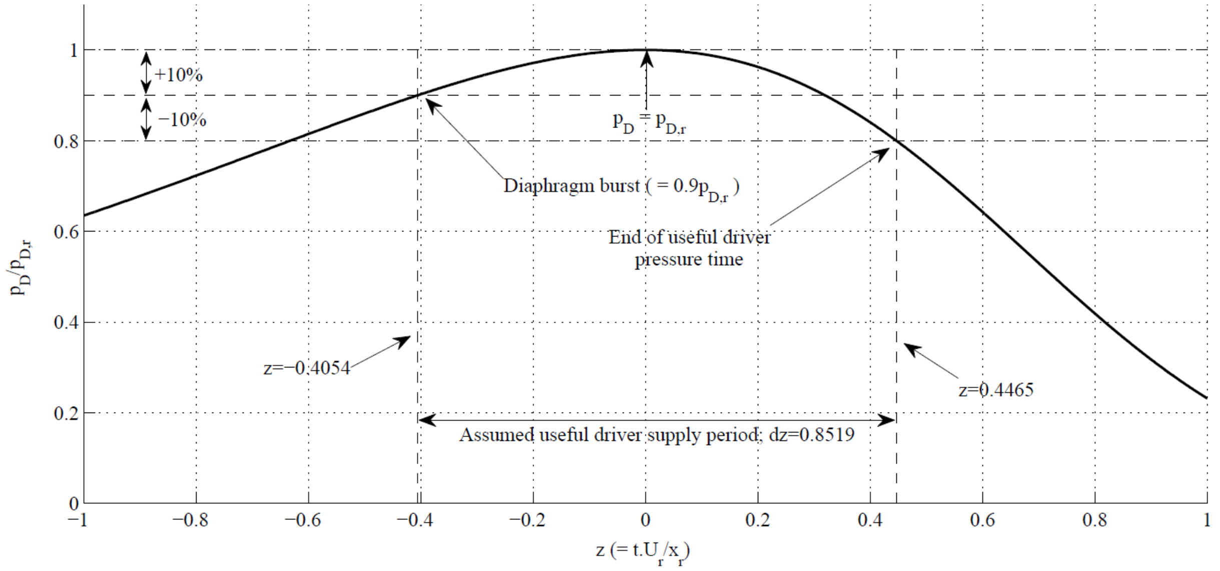


Figure 27. Rupture pressure analysis for ±10% permissible pressure variation (k = 1, taken from [34])

With the analysis done above and *z* value solved, we can further apply the further steps developed by Gildfind in 2012 [34] to determine a necessary piston mass.

From Figure 27, when $k = 1$, z values are -0.4054 and 0.4465 and the calculated z variation $\Delta z = 0.8519$. Thus, the time variation corresponding to z variation is:

$$\Delta t = \Delta z \cdot \frac{x_r}{U_r} = 0.8519 \frac{x_r}{U_r} \tag{5}$$

The piston speed should be calculated by the following equation when rupturing under condition developed by ±10% driver pressure variation analysis.

$$u_{rupture} = (1 - 1 \times -0.4054) \cdot U_r = 1.4054 U_r \tag{6}$$

The U_r in the above equation, which is the piston speed at condition r defined in the previous paragraph within this section, can be calculated by:

$$U_r = \left(\frac{2}{\gamma_D + 1}\right)^{\frac{(\gamma_D+1)}{2\cdot(\gamma_D-1)}} \cdot \left(\frac{A_*}{A}\right) \cdot \sqrt{\gamma_D \cdot R_D \cdot T_{D,0} \cdot \left(\frac{p_{D,r}}{p_{D,0}}\right)^{\frac{\gamma_D-1}{\gamma_D}}} \tag{7}$$

Then, for a 10% driver pressure variation, the compression ratio following primary diaphragm rupture needs to be calculated:

$$\lambda_r = \frac{\lambda}{0.9^{\frac{1}{\lambda}}} \tag{8}$$

The later steps to determine the necessary piston are realised through iterating desired piston mass. Each iteration tries a piston mass with a reservoir initial filling pressure calculated. The desired piston mass can fulfil the condition when the piston speed at rupture (previously determined by the ±10% variation analysis) has a value equal to $1.4054U_r$. This iteration process, summarised below, was clarified by Gildfind in 2012:

- Choose a piston mass;
- Calculate initial reservoir fill pressure $p_{A,0}$ using the following equation:

$$p_{A,0} = \left(p_{D,r} - \frac{m_p \cdot U_r^{\,2} \cdot k \cdot \lambda_r}{L \cdot A}\right) \cdot \left[1 - \frac{\gamma_A - 1}{2} \cdot \left(\frac{u}{a_{A,0}}\right)\right]^{\frac{-2 \cdot \gamma_A}{(\gamma_A - 1)}} \tag{9}$$

- Calculate piston dynamics, $u_{rupture}$ *and* $x_{rupture}$ *using the equations below:*

$$\frac{du}{dt} = \frac{A}{m_p} \cdot \left\{p_{A,0} \cdot \left[1 - \frac{\gamma_A - 1}{2} \cdot \frac{u}{a_{A,0}}\right]^{\frac{-2 \cdot \gamma_A}{\gamma_A - 1}} - p_{D,0} \cdot \left(\frac{L}{x}\right)^{\gamma_D}\right\} \tag{10}$$

$$x_{rupture} = \left(\frac{p_{D,0}}{p_{D,rupture}}\right)^{\frac{1}{L}} \tag{11}$$

- Iterate the process until this condition is fulfilled when $k = 1$:

$$u_{rupture} = 1.4054 \cdot U_r$$

To conclude, to ruin a Stalker Analysis, the input parameters are:

- Compression ratio;
- Driver and reservoir gas compositions;
- Compression tube area;
- Primary diaphragm rupture pressure.

And the output parameters are:

- Piston mass;
- Initial reservoir filling pressure.

3.1.3 Hornung' Theory – Driver Piston Motion

Hornung's theory proposes an analytical method to evaluate the performance of a compression tube with two main stages divided - before and after the rupture of primary diaphragm. The equation of piston motion given by Hornung's research report is [30]

$$-M_p \cdot \frac{d^2x}{dt^2} = \frac{\pi \cdot D^2}{4} \cdot \left\{ p_{A_0} \cdot \left(1 - \frac{\gamma_A - 1}{2} \cdot \frac{u}{a_0}\right)^{\frac{2\gamma_A}{\gamma_A - 1}} - p_{H_0} \cdot \left(\frac{L}{x}\right)^{\gamma} \right\} \tag{12}$$

Where, M_p is the piston mass, D is compression tube diameter, t is time from piston release, p_{A_0} is the initial pressure in the air, initial pressure in the helium is p_{H_0}, piston speed is u, initial distance of the piston from the diaphragm is L with variable value x, a_0 is the initial speed of sound in the air and γ_A is the specific heat in the air.

The piston motion equation was manipulated to generate several coefficient-based charts to reflect the performance of the driver in 1988 [30]. However, his theory is based on an important assumption (an ideal model) that the length of the compression tube behind the piston is infinite, which means there is no reflection of waves behind the moving piston.

3.2 Compression Tube Design

The review of tuned operation in section 0 indicates that a long compression tube would be able to ease the requirement of tuning a piston, which means it would be not strict to require a relatively lighter piston as there is longer distance for the driver piston to accelerate and decelerate [8].

Some recommendations of compression tube design are listed below which were summarised by UQ researcher Gildfind in 2012 [34]:

- Maximise compression tube diameter to achieve a large area-change at the primary diaphragm;
- Compression tube diameter shall be at least 3 times larger than that of the driven tube;
- Maximise the length of the compression tube as possible;
- A relatively high pressure-rating is recommended;

Li and Lü et al. [36] of China Aerodynamics Research and Development Center (CARDC) in 2016 talked about the optimal relationship of Compression Tube Length and Diameter with the combination of some previous theories about free-piston driver, which used numerical analysis method to discuss compression tube design and optimizing process. Finally, the conclusion from Li and Lü et al. ends to:

- Under specific compression ratio, for Compression Tube, the longer the “better”;
- The higher the L/D is, the easier to have constant driving pressure after primary diaphragm rupture (analysis given within the paper);

- The best combination of compression tube diameter and length shall consider the upper lab space with cost dominated.
- (Note: Driver condition for above analysis: 100% H2; 85% H2 + 15% N2; 100% He; 85% He + 15% Ar).

Furthermore, for performance predication of a compression tube, Hornung's theory proposes a theory to analysis the performance of compression tube and the piston motion [30], which could help to effectively analyze the performance of a designed compression tube.

3.3 Inertia Mass

For free-piston driven impulse facilities, an inertial mass is always needed to be placed at the end of compression tube or the junction between compression tube/shock tube, which can significantly reduce the recoil motion of the facility after a shot [23].

In order to highlight the importance of inertia mass, consider the case when piston directly hits the end of compression tube, which can be simplified into a model that a cylinder mass (assumed to be rigid) impacts into an elastic hollow bar. The rough tensile elastic stress might be:

$$\sigma = V_{overall} \cdot \sqrt{\rho \cdot E} \tag{13}$$

Where,

- $V_{overall}$ – The together departure speed of piston and tube after impact;
- E – Young's modulus of tube materials;
- ρ – Density of tube materials.

If we assume the tube material density and Young's modulus are 8050 kg/m^3 and 200 GPa respectively with a 0.5 m/s $V_{overall}$ after impact. The tensile elastic stress might be:

$$\sigma = V_{overall} \cdot \sqrt{\rho \cdot E} = 0.5 \times \sqrt{8050 \times 210 \times 10^9} = 20.56 \frac{MPa}{m/s}$$

This result points a rough correlation that the tensile stress caused by the impact may increase approximately 20.56 MPa for every 0.5 m/s rise of $V_{overall}$. If we set that this stress caused by impact cannot exceed 350 MPa, it indicates that the $V_{overall}$ shall be lower than 8.512 m/s.

Then, consider the momentum conservation law:

$$\mathrm{m_{piston}} \times \mathrm{V_{impact}} = (\mathrm{m_{piston}} + \mathrm{m_{inertial}}) \times \mathrm{V_{overall}} \tag{14}$$

Hence, the facility inertial mass shall at least be (for a 350 m/s impact):

$$m_{inertial} = \frac{m_{piston} \times V_{impact}}{V_{overall}} - m_{piston} \approx \frac{m_{piston} \times V_{impact}}{V_{overall}} = \frac{m_{piston} \times 350}{8.512}$$

$$= 41.12 \cdot m_{piston}$$

Please note that this calculated result still needs related safety factors to be applied.

Case study:

- The T5 shock tunnel has a 14-tonne inertial mass and 120-150 kg pistons.
- The HEG shock tunnel has an approximately 90-tonne inertial mass and 760 kg piston.

3.4 Primary diaphragm rupture pressure.

The maximum limit rupture pressure of the primary diaphragm is determined by pressure rating of driver. For tuned operation of driver, the following factors significantly influence the performance of driver [34]:

- The primary diaphragm rupture pressure;
- The compression ratio at rupture;
- The driver gas specific gas constant;

In the compression tube, without the primary diaphragm, the released piston firstly has positive downstream acceleration until the pressure difference is zero in front of and behind the piston. After the equilibrium point, the piston begins to slow down with negative upstream acceleration with continuing compressing the driven gas in front of the piston. When the speed of piston reaches zero, the compressed driven gas has the highest temperature and pressure during the compression stage. After the zero-speed point, the piston begins to be bounced back.

However, the desired operating pressure is not the peak pressure mentioned at zero-speed point mentioned in the above paragraph. The ideal working condition after rupturing is to let the gas flow from compression tube to shock tube equal to the gas flow continuously pushed by piston with a remaining speed, which is always regarded as a relatively quasi-constant motion.

Normally, to reach a quasi-constant driver pressure for a sufficient duration is what we want [30]. Thus, a diaphragm at the end of the compression tube is needed to be ruptured at a specific time after the launch of piston.

3.5 Facility Modelling with L1D

L1D developed by P. Jacobs, can simulate transient-flow facilities such as free-piston driven shock tubes. The L1D uses a numerical modelling method based on Quasi-one-dimensional Lagrangian description of the gas dynamic. Meanwhile, it was coupled with engineering correlations for viscous effect and point-mass dynamics for piston motion [37]. L1D is the basic tool to predicate the performance of X4 with building analytical models.

In 2005, P. Jacobs produced another department technical report of using Python written program l_script.py to set up a simulation in L1D as it is intended for the user to define their particular facility and flows in terms of the data objects defined in this module [38]. During the initialization of l_script.py, a particular user job file will be constructed, which contains the user's code that defines both facility geometry and gas-path details in Python.

It is not of strict necessity for this project to use L1D to predict the performance of one of the sets of design.

3.6 Tube Wall Thickness Calculation

Australian Standards 4041-2006_R2016 Pressure Piping gives this project a guidance of the calculation of tubes wall thickness.

The methods of calculation of AS 4041-2006 are sometimes based on the ASME B31 series of Standards [39]. This section is going to review the method and clarify the important parameters used for the calculation of tube wall thickness according to AS 4041-2006_R2016. Meanwhile, we should hold a critical attitude towards the results calculated by this method as the targeting industry and working condition introduced by AS 4041-2006 have significant difference with X4's lab using environment.

3.6.1 Design Pressure

The design pressure is defined as the highest differential between the internal and external pressure that will occur in normal operation [39].

During the whole process of a shot in an expansion tube, for driver, the highest pressure is dominated by the diaphragm rupturing pressure, thus, the primary diaphragm rupturing pressure shall be considered as the design pressure for determining the wall thickness of compression tube. Meanwhile, safety factor shall participate in the calculation.

For example, the JAXA HEK-X had a 1 ms test time under conditions with 55 MPa primary diaphragm rupture with the design maximal tube pressure of 130 MPa [10].

3.6.2 Design Temperature

The design temperature of piping material shall be taken to be the temperature of the fluid if the internal fluid is less than 40°C [39].

3.6.3 Design Strength

The value of the design strength shall be appropriate for the material and other design considerations.

Compressive Stress for Tube and Pipe

The value of the stress in compression shall be appropriate for the material and design temperature ensuring structural stability and shall not exceed the design strength in tension [39].

Shear Stress

The value of any primary shear stress shall be appropriate for the material and design temperature, which shall be 60% of the tensile design strength [39].

Bearing Stress

The value of the stress in bearing shall be appropriate for the material and design temperature and shall not exceed 160 percent of the design strength in tension [39].

3.6.4 Design Factors

There are several design factors considered for pressure piping design which are listed below:

- Weld Joint Factor;
- Class Design Factor;
- Casting Quality Factor;
- Weld Joint Strength Reduction Factor;

Explanations and factor table for selecting are summarised in Appendix 3.

3.6.5 Allowances

The wall thickness reduction of pipe shall be compensated by an amount equal to the allowance (G). Several reasons are proved to have the impact:

"Corrosion, erosion, threading, or grooving, or to add mechanical strength and any other necessary parameters are considered to be compensated by allowance (G)" [39].

Some contributing aspects to allowances are summarised below:

- Manufacturing tolerances;
- Corrosion or erosion;
- Threading, grooving or machining;
- Extra mechanical strength;

For normal allowances needed for a certain engineering condition, the database from pressure piping design handbook plays an important role to determine the final G value.

3.6.6 Wall Thickness Calculation of Straight Pipe

Required Wall Thickness

$$t_m = t_f + G \quad (15)$$

where,

- t_m– Required Wall Thickness
- t_f – Pressure Design Wall Thickness
- G – Allowances

The nominal wall thickness shall be the summation of required wall thickness and manufacturing tolerance provided by supplier.

Pressure Design Wall Thickness for Pipe under internal pressure

Where the design wall thickness is less than D/6, the pressure design wall thickness shall be determined from equation below:

$$t_f = \frac{pD}{2feMW + p} \quad (16)$$

Where,

- D - Outside diameter (mm);
- M – Class Design Factor (Appendix 3.2);
- f – Design Strength (MPa);
- p – Design Pressure (MPa);
- t_f – Pressure Design Wall Thickness (mm);
- W – Weld Joint Reduction Factor (Appendix 3.4);
- e – Weld Joint Factor (Appendix 3.1);

Chapter 4 X4 Design Guidelines

4.1 Assistance to Perform a Design

Design an expansion tunnel is complex, a software with analytical models integrated might be extremely beneficial to assist a conceptual design. A program, developed by the author, is demonstrated in Chapter 5 guiding the user to perform a step-by-step preliminary design of a free-piston expansion tube facility. The remainder of this chapter is to provide design guidelines.

4.2 The Maximum Total Length of X4

Put the result in the beginning, the allowable maximum total length is 65 meters.

During years of operation experiences of expansion tubes, scientific evidence and research results indicate that size is paramount for expansion tubes: a longer tube provides more test time and a larger tube diameter suits testing of larger models [1]. Meanwhile, the critical relationship between facility scale and cost needs to be considered because a slight increase of dimension might cost extra millions of dollars on budget. The theories reviewed in section 3.2 indicate that a balance shall be found between the overall facility cost and the facility dimension.

One of the most important requirements of X4 development is to avoid the high operation and construction cost as X3. Thus, even though the relocation of X3 permits a 70-meter long space availability and gives the possibility of building another large-scale facility, it is not recommended to let X4 beyond human-manual operation scale. Figure 28 below demonstrates the lab space availability for X4 (red rectangular framed area).

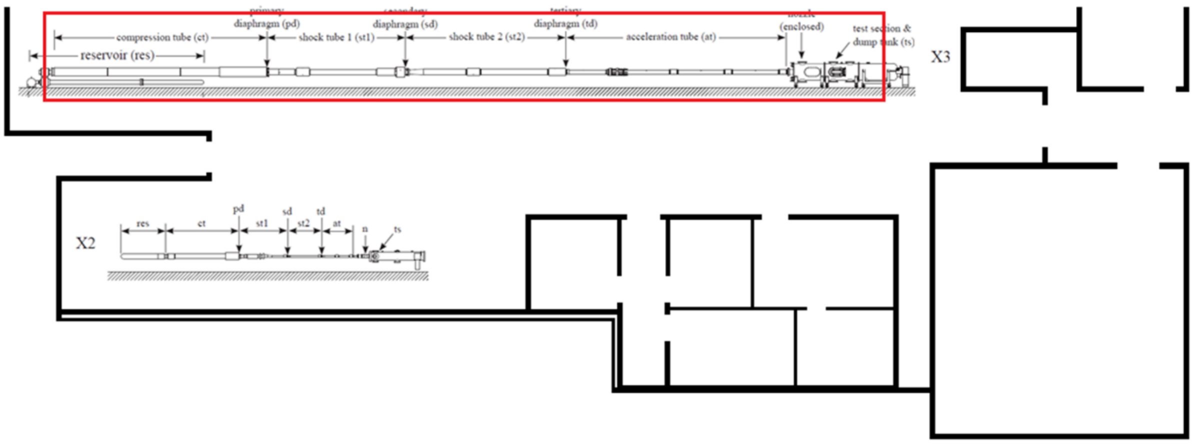


Figure 28. Demonstration of lab space availability for X4 (not drawn precisely by scale)

4.3 Compression Tube Diameter

The author uses a parametric method to have the dimension model built on the base of compression tube diameter. Thus, compression tube diameter is the base variable to construct the set of equations to verify the dimension parameters.

According to the design requirements on dimension and the literature reviews, the compression tube initial wanted diameter range was determined to 330 – 720 mm. Thus, the later analysis of other dimension parameters will be based on this range which are listed below:

- Compression tube length;
- Shock tube diameter;
- Shock tube length;
- Acceleration tube diameter;
- Acceleration tube length;
- Tube wall thickness;
- Total length.

To sum up,

Compression tube proposal bore range (unit: millimetre):

$$CT_{Diameter} = (330{,}630) \tag{17}$$

4.4 Compression Tube Length

One of the important parameters of free-piston driven expansion tubes is the ratio of compression tube length over compression tube diameter. Hornung used the ratio in 40, 60 and 100 in 1988 [30] to demonstrate his non-dimensional analysis on piston motion in a sequence of charts. Based on the investigations of free-piston driven expansion tubes Chapter 2 of this essay, the ratio (compression tube length over compression tube diameter) is always in a range from 20 to 100.

Because of the lab space availability, we set the range of compression tube dimension ratio:

$$CT_{LDratio} = (20, 70) = \frac{CT_{Length}}{CT_{Diameter}} \tag{18}$$

Thus, the proposal length range of compression tube is,

$$CT_{Length} = CT_{Diameter} \cdot CT_{LDratio} \tag{19}$$

Finally, the initial proposal length range of compression tube is from 6600 to 44100 mm.

4.4.1 Gradual-thick Compression Tube

After the launch of piston for a shot, the driver gas is gradually compressed within compression tube and in front of the piston face as a time scale of tens of milliseconds. Logic indicates that the upstream part bears lighter gas compression load than the downstream part of compression tube. Thus, it is recommended to use tube sections with lower thickness in the upstream half of compression tube, which could significantly reduce the overall facility cost. As Case Study 4 in Chapter 9 indicates that the 17.3% to 21.65% facility cost contributed by driver as facility scale increasing from 20-meter scale to 67-meter scale.

By applying the gradual-thick method, it could be expected that 4.32% - 8.21% overall facility material cost could be brought down.

4.4.2 Extendable Compression Tube Length

It is suggested that building the compression tube with the ability to be extended in the future if a larger space availability permits the pursuit of higher facility performance and wider simulating capability.

The HELM shock tunnel is a typical facility to designed in a way that both the driver and the shock-tube length can be varied. This is achieved by a its modular design philosophy. Its tube sections are installed on moveable connections [25].

4.5 Shock Tube Diameter

The years of operation free-piston driven impulse facility at UQ gave the recombination that the diameter of compression tube would better be 3 times larger than that of the shock tube.

Meanwhile, most free-piston driven impulse facilities chose this ratio to be around 3. A comparison and summary are given below with main free-piston driven impulse facilities' ratio summarised (ratio: compression tube diameter over shock tube diameter):

Table 9. Summary of ratio (Compression Tube diameter over Shock Tube diameter)

Facility	Location	CT_D (Diameter of Compression Tube, mm)	ST_D (Diameter of Shock Tube, mm)	CT_D/ST_D
Expansion Tube				
X2	UQ, Australia	256.8	85	3.021
X3	UQ, Australia	500	180	2.778
HEK-X	JAXA, Japan	210	72	2.917
JX-1	JAXA, Japan	150	50	3
Shock Tunnel				
Facility	Location	CT_D (Diameter of Compression Tube, mm)	ST_D (Diameter of Shock Tube, mm)	CT_D/ST_D
T4	UQ, Australia	229	76	3.013
T5	Caltech, USA	300	90	3.333
T6	Oxford Uni, UK	300	96.3	3.115
FD21	CAAA, China	668	290	2.303
HEG	DLR, Germany	550	150	3.667
HELM	UAFM, Germany	286	95	3.011
HIEST	JAXA, Japan	600	180	3.333

Hence, the ratio that the author would like to recommend is,

$$\frac{CT_{Diameter}}{ST_{Diameter}} = 3 \tag{20}$$

Thus, the proposal diameter range of shock tube is from 110 to 210 mm.

4.6 Shock Tube Length

A comparison and summary are given below in Table 10 with main free-piston driven impulse facilities' ratio summarised (ratio: compression tube length over shock tube length):

Table 10. Summary of ratio (Compression Tube length over Shock Tube length)

Facility	Location	CT_L (Length of Compresstion Tube, m)	ST_L (Length of Shock Tube, m)	CT_L/ST_L
Expansion Tube				
X2	UQ, Australia	3.8	3.424	1.11
X3	UQ, Australia	14	22	0.636
HEK-X	Kakuda, Japan	16	6.5	2.462
JX-1	JAXA, Japan	3	1.8	1.667
Shock Tunnel				
Facility	Location	CT_L (Length of Compresstion Tube, m)	ST_L (Length of Shock Tube, m)	CT_L/ST_L
T4	UQ, Australia	26	10	2.6
T5	Caltech, USA	30	12	2.5
T6	Oxford Uni, UK	6	6	1
FD21	CAAA, China	75	35	2.143
HEG	DLR, Germany	33	17	1.941
HELM	UAFM, Germany	21	8,9,10,11	2.625, 2.333, 2.1, 1.9
HIEST	JAXA, Japan	42	17	2.471

4.7 Acceleration Tube

There were several facilities configured from shock tunnel to expansion tube with the addition of an acceleration tube and minor length manipulation of other tube sections. Methodology of designing the acceleration tube could be inherited from experiences of facilities with ability to be configured from shock tunnel to expansion tube/tunnel like the HYPULSE-SET/RST and HEK-X.

4.7.1 Acceleration Tube Diameter

Acceleration Tube and Shock Tube of most expansion tube facilities have same diameter.

4.7.2 Acceleration Tube Length

A comparison and summary are given below in with main free-piston driven impulse facilities' ratio summarised (ratio: Acceleration Tube length over Shock Tube length):

Table 11. Summary of ratio (Acceleration Tube length over Shock Tube length)

Expansion Tube Facilities				
Facility	Location	AT_L (Length of Acceleration Tube, m)	ST_L (Length of Shock Tube, m)	AT_L/ST_L
X2	UQ, Australia	5.155	3.424	1.51
X3	UQ, Australia	25	22	1.14
HEK-X	Kakuda, Japan	9.4	6.5	1.45
JX-1	JAXA, Japan	2.6	1.8	1.44
HYPULSE - SET	GASL, USA	12.63	5.09	2.48
HET	Caltech, USA	3.96	3.96	1.00
HXT	Texas A&M,USA	15.2	4.6	3.30
JF16	CAS, China	4.34	2.84	1.53

4.8 Piston Mass

The Stalker Analysis reviewed in Section 3.1.2 is the methodology to determine the necessary piston mass for X4 with tuned operation.

MATLAB was used to develop an analytical model based on Stalker's non-dimensional relationship between driver gas density and time. Stalker Analysis was also integrated into the program introduced in Chapter 5 to determine a necessary piston mass for one set of design with some operation condition parameters assumed.

4.9 Inertial Mass

X4 aims to be "human-manual-operation" scale, which derives that the driver piston mass of X4 would not exceed 200 kilograms.

The mathematical derivation and analytical model in section 3.3 offers a methodology to calculate the necessary inertial mass based on the necessary piston mass. This method can permit a safety operation condition if the facility-wide impact-caused moving velocity is set to an at-low-risk level (e.g. less than 9 m/s).

However, one defect of this methodology is, the calculated inertial mass only permits a piston mass lower than the piston mass used within the calculation process.

Chapter 3.3 talked about the analytical relationship about inertial mass calculation and the related permitted piston mass, which is converted into program code in 5.4.

Chapter 5 Development of a Design Tool

A tool named Free-piston Expansion Tube Calculator was developed by the author to assist the conceptual design of X4 or any other free-piston expansion tubes.

For this thesis, it is not actually necessary to deliver one set of specific design of X4. Meanwhile, it would be extremely useful if there would be some helpful tools for the future formal design and construction of X4. Thus, this program based on Python was developed, which integrated several significant and useful expansion tube analytical methods.

This program mainly comprises of the following listed modules to assist a conceptual design for a Free-piston Expansion Tube:

- Dimension Calculator;
- Tube Wall Thickness Calculator;
- Necessary Piston Mass Calculator;
- Necessary Inertia Mass Calculator;
- Rough Cost Calculator (Cost model);

This chapter introduces this tool without an actual run to get calculated results. In order to help better clarify how to use this program, most of the parameters will be demonstrated in number 0. For the actual runs and case study of this program, please refer to Chapter Chapter 7 and Chapter 9 .

5.1 Dimension Calculator

5.1.1 Function

When running the program, the first GUI window requires the user to input 4 parameters:

- Proposal Diameter of Compression Tube in millimetre;
- Proposal Length of Compression Tube in millimetre;
- Proposal Ratio of Diameter ($\frac{Diameter\ of\ Compression\ Tube}{Diameter\ of\ Shock\ Tube}$);
- Proposal Ratio of Length ($\frac{Diameter\ of\ Compression\ Tube}{Diameter\ of\ Shock\ Tube}$).

Please note that the “diameter” here refers to the bore parameter of a tube, which indicates the effective inner flow dimension.

For the ratios required to be inputted here, the author gives a recommendation parameter which are only for reference when using this program. Figure 29 is screen-shot of this step.

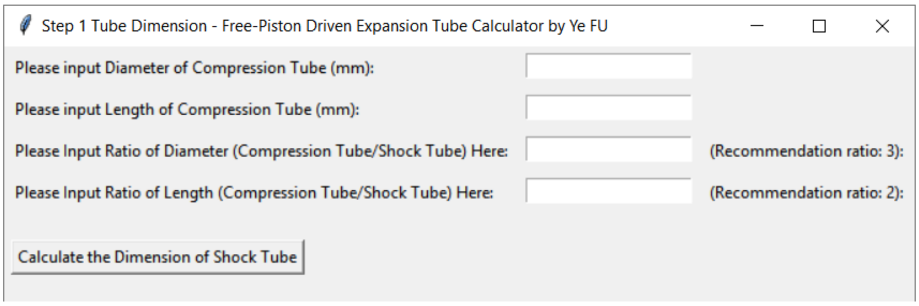


Figure 29. First GUI window of Step 1 Tube Dimension (input)

After inputting the initial parameters and click the "calculate" button, the calculated dimension of Shock Tube will be shown with the next-step input instructions given. This following step requires the user to input proposal ratios of dimension relationship between Acceleration Tube and Shock Tube.

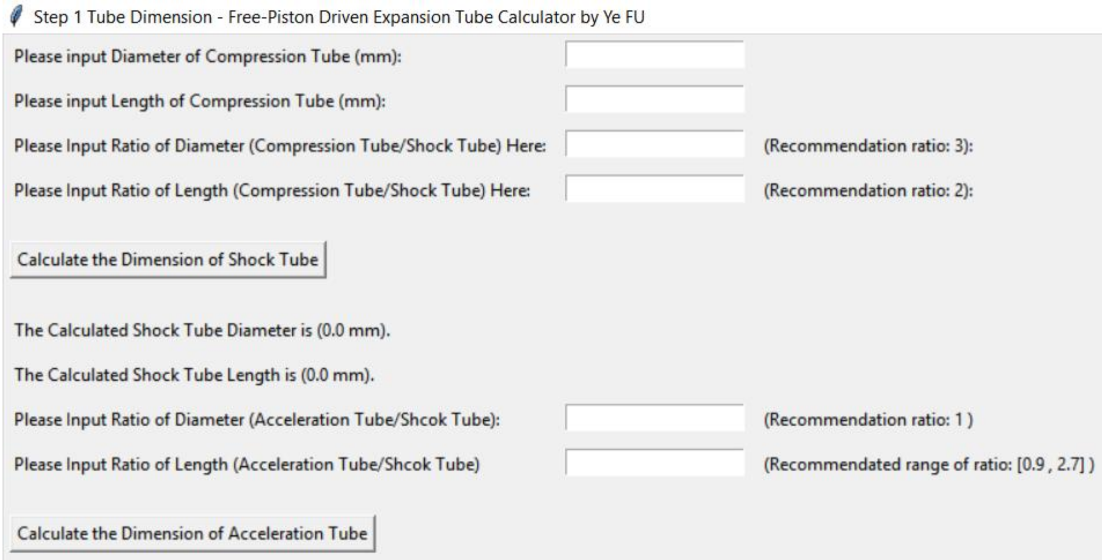


Figure 30. Second GUI window of Step 1 Tube Dimension (CT dimension output and further input)

After inputting the ratios required to calculate the dimension of Acceleration Tube and click the "calculate" button, the calculated results will be shown followed by a button to notice the user to demonstrate the overall dimension results of this run. Figure 30is the screen capture of this step.

Continuously, when clicking this "demonstrate" button, besides demonstrating the dimension results of tube sections, the dimension information will also be transferred to the later steps for further analysis. The total length of this step only refers to the length sum-up of CT, ST and AT. Realistically, test section and reservoir contribute to the total length of facility significantly as well. Figure 31 is the window shot of this step.

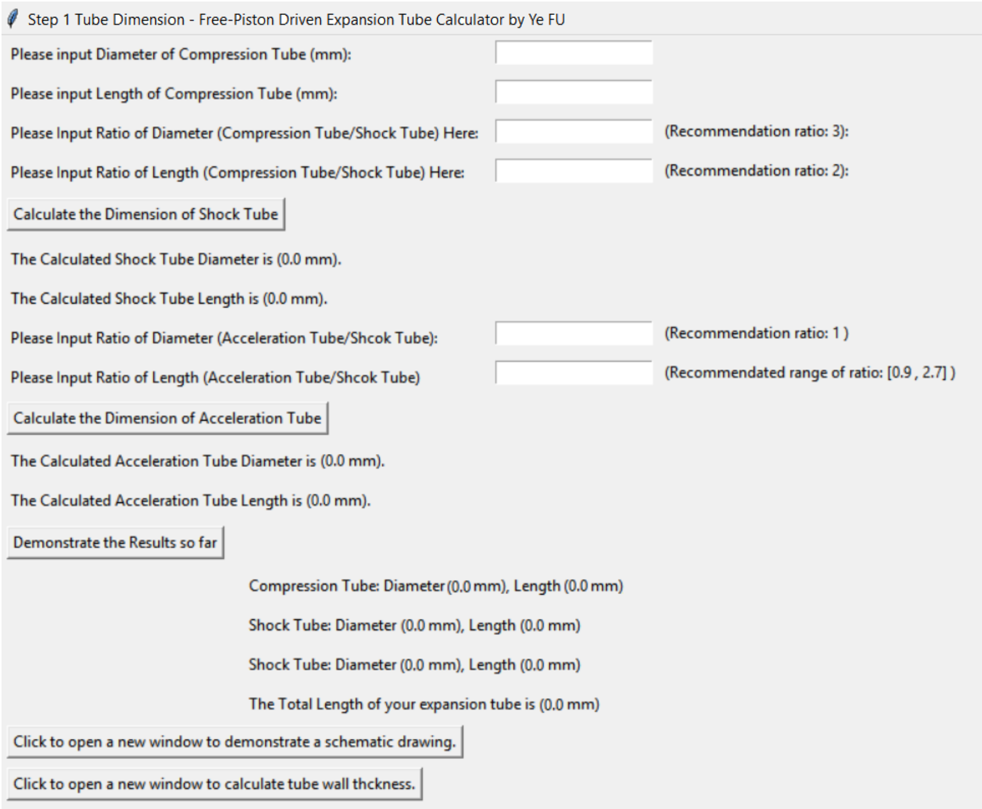


Figure 31. Final GUI window of Step 1 Tube Dimension (dimension demonstration)

Finally, the last two buttons of step 1 are shown in Figure 31. One of the buttons is to demonstrate a schematic drawing of the expansion tube dimension of this run. The other one of the buttons is to open the step 2 – calculation of tube wall thickness.

5.1.2 Core Code

Code of this module is mainly about the realisation of GUI to input initial parameters, for details please refer to Appendix A.

5.2 Tube Wall Thickness Calculator

5.2.1 Function

After clicking the “Click to open a new window to calculate tube wall thickness.” Button, the Step 2 GUI window will be appearing (Figure 32), which requires the user to input the set of parameters for tube wall thickness calculation.

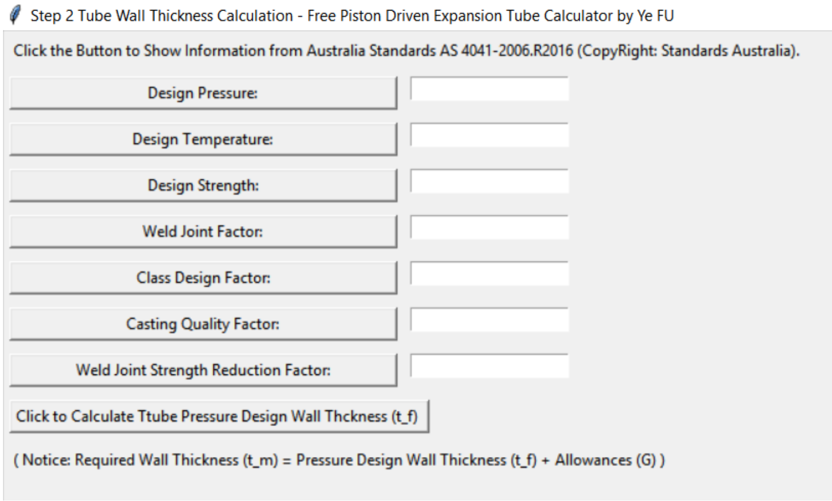


Figure 32. First window of Step 2 Tube Wall Thickness Calculation (input)

With the initially inputted parameters, after clicking the "calculate t_f" button, the window in will be shown. This step calculates the "t_f" which is a pressure-design wall thickness. To calculate the required wall thickness "t_m", parameter G (allowances) is needed. The step window in Figure 33 shows that blank spaces are provided to the user to input the desired Gs.

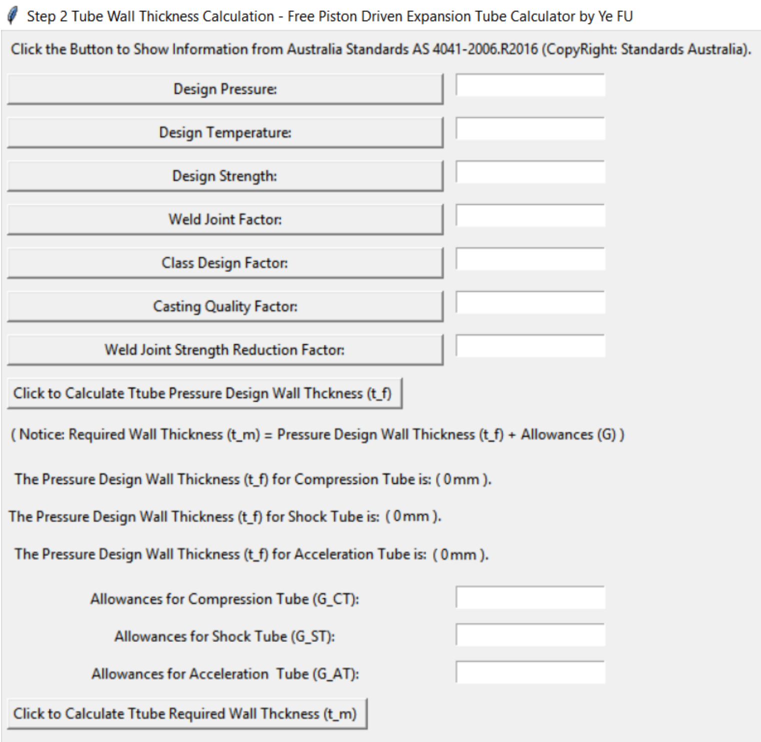


Figure 33. Second window of Step 2 Tube Wall Thickness Calculation (t_f shown with G input required)

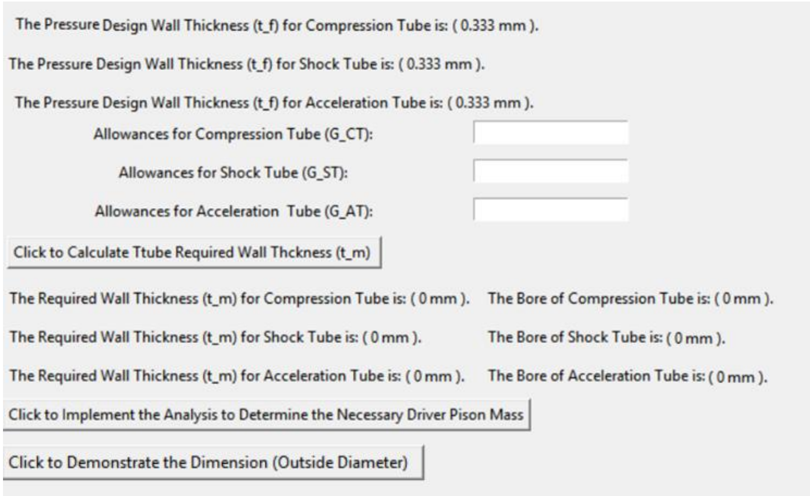


Figure 34. Results window of Step 2 Tube Wall Thickness Calculation

In the final window of this step, required tube wall thickness and dimension sets in outside diameter of each tube section are demonstrated. If we click the final button named “Click to Implement the Analysis to Determine the Necessary Driver Piston Mass”, calculation results will be transferred to the later steps and the Step 3 window will be open to assist the user to determine a necessary piston mass of this run based mainly on the theories proposed by Professor Stalker.

5.2.2 Core Code

This section demonstrates the core code to realise this module, spaces between lines are removes. Please refer to Appendix for more details.

```python
def TFcalculateWT():
  global CT_TF
  global ST_TF
  global AT_TF
  # let's get the inputted parameters
  DesignPressure = float(CWT.InputDesignPressure.get())
  DesignTemp =  float(CWT.InputDesignTemp.get())
  DesignStrength = float(CWT.InputDesignStrength.get())
  WeldJointFactor = float(CWT.InputWeldJointFactor.get())
  ClassDesignFactor = float(CWT.InputClassDesignFactor.get())
  CastingQualityFactor = float(CWT.InputCastingQualityFactor.get())
  WeldJointStrengthReductionFactor = float(CWT.InputWeldJointStrengthReductionFactor.get())
  CT_TF = round((DesignPressure*float(ETDimension[0]))/(2*DesignStrength*WeldJointFactor*ClassDesignFactor*WeldJointStrengthReductionFactor+DesignPressure),3)
  ST_TF = round((DesignPressure*float(ETDimension[1]))/(2*DesignStrength*WeldJointFactor*ClassDesignFactor*WeldJointStrengthReductionFactor+DesignPressure),3)
  AT_TF = ST_TF
  # to add some line margins in GUI
  Give_the_results_some_space_ok = Label(CWT,text = '').grid(row=10,column=0,padx=5,pady=5,sticky=NW)
  # demonstrate the calculation results of wall thickness for ct st and at
  Label(CWT,text = ' The Pressure Design Wall Thickness (t_f) for Compression Tube is: ( %s mm ).'%CT_TF).grid(row=13,column=0,columnspan=2,padx=5,pady=5,sticky=NW)
  Label(CWT,text = ' The Pressure Design Wall Thickness (t_f) for Shock Tube is: ( %s mm ).'%ST_TF).grid(row=14,column=0,columnspan=2,padx=0,pady=5,sticky=NW)
  Label(CWT,text = ' The Pressure Design Wall Thickness (t_f) for Acceleration Tube is: ( %s mm ).'%AT_TF).grid(row=15,column=0,columnspan=2,padx=5,pady=5,sticky=NW)
  # to add some line margins in GUI
  Give_the_results_some_space_ok = Label(CWT,text = '').grid(row=17,column=0,padx=5,pady=5,sticky=NW)
  LabelAllowancesCT = Label(CWT,text = 'Allowances for Compression Tube (G_CT):').grid(row=19,column=0,padx=5,pady=5,sticky=E+W)
  CWT.InputAllowancesCT= Entry(CWT)
  CWT.InputAllowancesCT.grid(row=19,column=1,padx=5,pady=5,sticky=NW)
  LabelAllowancesST = Label(CWT,text = 'Allowances for Shock Tube (G_ST):').grid(row=20,column=0,padx=5,pady=5,sticky=E+W)
  CWT.InputAllowancesST = Entry(CWT)
  CWT.InputAllowancesST.grid(row=20,column=1,padx=5,pady=5,sticky=NW)
  LabelAllowancesAT = Label(CWT,text = 'Allowances for Acceleration  Tube (G_AT):').grid(row=21,column=0,padx=5,pady=5,sticky=E+W)
  CWT.InputAllowancesAT = Entry(CWT)
  CWT.InputAllowancesAT.grid(row=21,column=1,padx=5,pady=5,sticky=NW)
  CalTMbutton = Button (CWT,text = 'Click to Calculate Ttube Required Wall Thckness (t_m) ', command = TMcalculateWT).grid(row=22,column=0,padx=5,pady=5,sticky=NW)
```

5.3 Necessary Piston Mass Calculator

5.3.1 Function

Figure 35 shows the window capture of initial GUI user interaction in Step 3, which instructs the user to input the k value of Stalker Analysis to provide a margin of safety for the design.

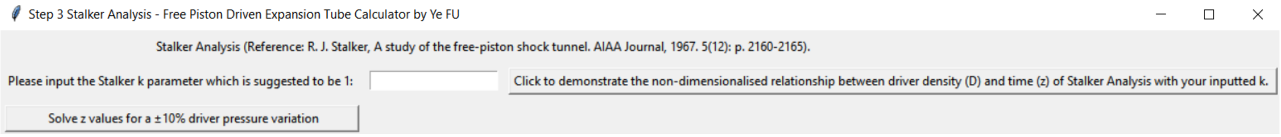


Figure 35. First GUI window of Step 3 – Stalker Analysis (k value pending)

Normally this k value is 1 as described in Chapter 3.1.2. If click the longest button in the window shown in Figure 35, a chart similar to Figure 26 will be demonstrated in a new window to reflect the non-dimensionlised relationship between driver gas density and value *z*. Even though this run does not have the dimension so far, this chart is still able to be generated as Equation (1) does not require dimension parameters.

After inputting the k value and clicking the “solve *z* value” button, the ±10% driver pressure variation analysis will be done (described in Chapter 3.1.2) and the new window will be shown as Figure 36.

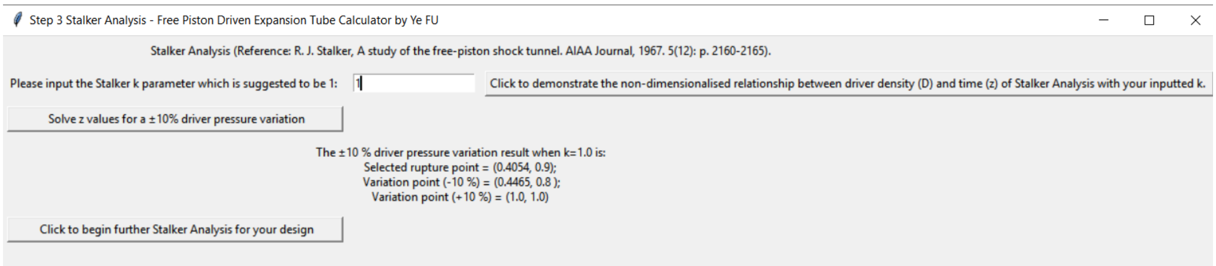


Figure 36. Second GUI window of Step 3 (demonstration of Equation 1 results)

After clicking “Click to begin further Stalker Analysis” button, a new window will be shown as Figure 37 to conduct the Stalker Analysis based on the inputted and calculated dimension for a run done by the user so far. For this run in this Chapter, this analysis cannot be done as we don’t have the significant compression tube dimension. Please refer to Chapter 7 for a comprehensive run of this program.

The Stalker Analysis done in Step 3 is an iterating process with proposal piston mass repeatedly inputted until the dynamics of piston (with inputted mass) fulfilling the requirements described in in Chapter 3.1.2. After inputting the following parameters, click the “test” button to verify whether piston mass of this run could fulfil the design requirements. However, unlike the methodology proposed by UQ researcher Gildfind in 2012 talked in Chapter 3.1.2, the author used a converse way – iterating Reservoir Filling Pressure until finding a piston mass. The main outputted parameter is a piston mass pending verification passes this test, a proposal reservoir filling pressure will be needed to be inputted.

- Compression ratio;
- Length between piston front face to compression tube end wall;
- Desired primary diaphragm rupture pressure;
- Driver gas ratio of specific heats;
- Reservoir gas ratio of specific heats;
- Driver filling pressure;
- Driver gas constant;
- Reservoir gas speed of sound;
- Desired tested Reservoir Filling Pressure.

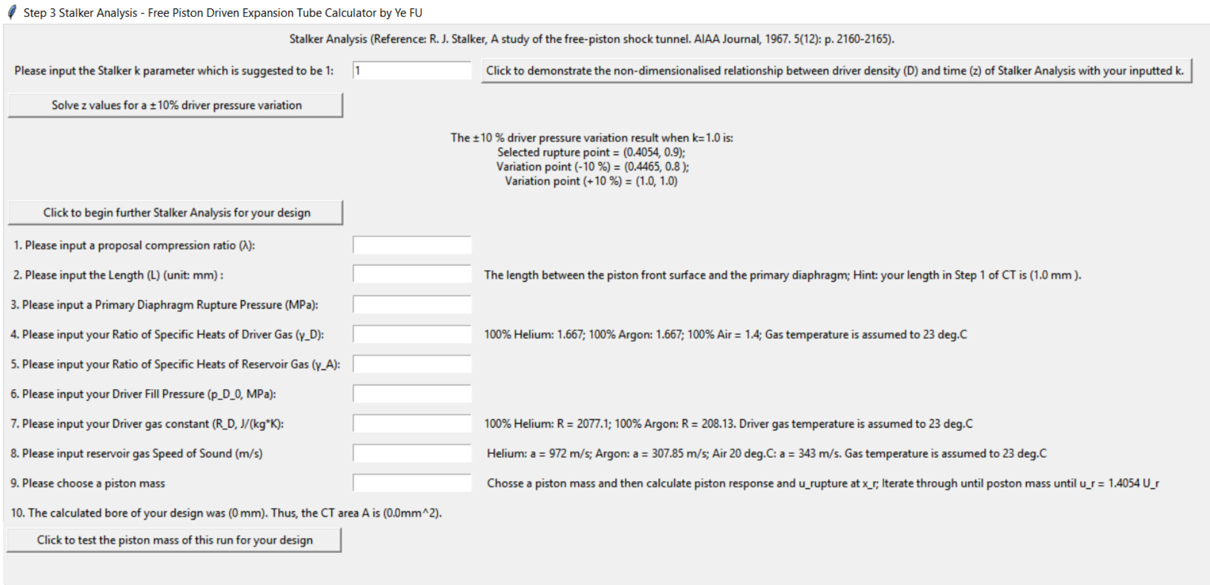


Figure 37. Stalker Analysis to determine piston mass, Step 3 (input GUI)

Finally, if the piston mass and calculated reservoir filling pressure are reasonable for the design of this run, click the "finish" button to open a new window of Step 4 with all the parameters directed to Step 4 and 5 for further analysis, Meanwhile, a ".txt" file will be generated as clicking the button to record all inputted and outputted parameters.

5.3.2 Core Code

This section demonstrates partial codes especially the analytical model developed by Professor Stalker, spaces between lines are removed. Please refer to Appendix C for more details.

```python
def plot():
    global k
    global D
    k = float(StalkerAnalysis.input.get())
    if k==1:
        z = numpy.arange(-1,1,0.01)
        qwe = numpy.arctan((k*z - 1)/((2*k-1)**(-1/2)))
        rty = numpy.arctan(-1/ (2*k-1)**(-1/2))
        uio = numpy.exp(-2 / (2*k-1)**(-1/2) * (qwe - rty))
        D = (1/(1 - z + ((z**2)* k/2))) * uio
        indicator1 = plt.axhline(0.9*max(D), color = 'r',linestyle ='--')
        indicator2 = plt.axhline(0.8*max(D), color = 'r', label ='±10% driver pressure variation indication line',linestyle ='--')
        indicator3 = plt.axhline(max(D), color = 'r', linestyle ='--')
    else:
        if k == 0.5:
            z = numpy.arange(-3,1.9,0.01)
            D = (1/(1 - z + ((z**2)* k/2)))
        else:
            z = numpy.arange(-3,1.9,0.01)
            qwe = numpy.arctan((k*z - 1)/((2*k-1)**(-1/2)))
            rty = numpy.arctan(-1/ (2*k-1)**(-1/2))
            uio = numpy.exp(-2 / (2*k-1)**(-1/2) * (qwe - rty))
            D = (1/(1 - z + ((z**2)* k/2))) * uio    #D = (1/(1 - z + ((z**2)* k/2))) * math.exp(-2 / ((2*k-1)**(-1/2)) * (numpy.arctan((k*z - 1)/((2*k-1)**(-1/2))) - numpy.arctan(-1/ ((2*k-1)**(-1/2)))))
    plt.title(' Non-dimensionalised relationship between driver density (D) and time (z) of Stalker Analysis when k = %s. '%k)
    plt.xlabel('z\nz = U_r * t / x_r', fontsize = 16)
    plt.ylabel('ρ_D / ρ_D,r', fontsize = 16)
    plt.plot(z, D)
    plt.grid(ON)
    plt.legend()
    plt.show()
    return D
...
U_r =round((((2/(RatioSpecificHeatDriver+1))**((RatioSpecificHeatDriver+1)/(2*(RatioSpecificHeatDriver-1))))* 9 * ((RatioSpecificHeatDriver*R_D*T_D_0*(RupturePressure/DriverFillPressure)**((RatioSpecificHeatDriver-1)/RatioSpecificHeatDriver))**(0.5)))**(0.5),3)
...
RuptureCompressionRatio = CompressionRatio / 0.9**(1/RatioSpecificHeatDriver) ##calculate rupture compression ratio, 0.9 is determined by the ±10 %% driver pressure variation
...
PistonMass = (RupturePressure - ReservoirFillPressure* (1- (0.5*RatioSpecificHeatReservoir-1)*(1.4*U_r/SpeedofSound))**(2*RatioSpecificHeatReservoir/(RatioSpecificHeatReservoir-1))) * (Length_m*float(ETDimension[0])*float(ETDimension[0])*numpy.pi/RuptureCompressionRatio/U_r/U_r)
...
```

5.4 Necessary Inertia Mass Calculator

5.4.1 Function

After finishing the previous 3 steps of the program, the facility inertial mass (placed at the junction between compression tube and shock tube) now can be calculated in the Step 4 of the program. The calculation theory was illustrated in Chapter 3.3 and the required parameters to accomplish the calculation are summarised below.

- The piston mass calculated in Step 3 (kg);
- The piston impact velocity (m/s);
- Tube section material strength (MPa);
- Tube section material Young's modulus (GPa);
- Tube section material density (kg/m^3).

The piston dynamics was calculated in Step 3 especially the piston velocity at desired primary diaphragm rupture pressure. This piston velocity $u_{rupture}$ can be used here as the impact velocity to provide a margin of safety. In order to increase the reliability of calculated results, this inertial mass calculation requires the user to input some of the calculated parameters in Step 3 rather than directly importing them. A comment/hint is given for the parameters calculated in previous steps. Figure 38 below is

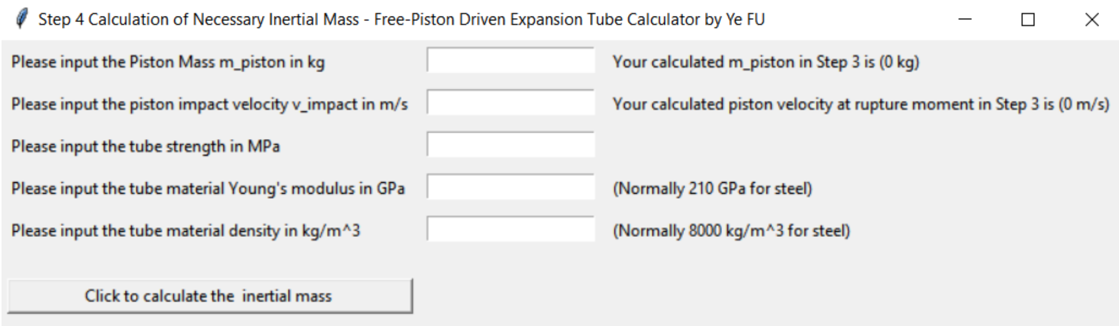


Figure 38. GUI for user to calculate the Inertial Mass in Step 4 (input)

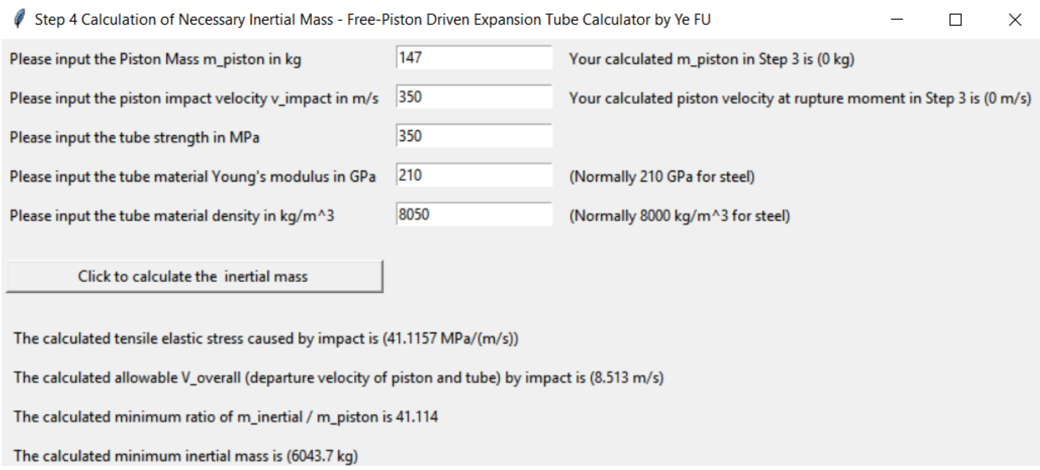


Figure 39. One test run of Step 4

5.4.2 Core Code

This section demonstrates partial codes especially the analytical model to calculate require inertial mass. Please refer to Appendix D for more details.

```
InertialMass = Tk()
InertialMass.title("Step 4 Calculation of Necessary Inertial Mass - Free-Piston Driven Expansion Tube Calculator by Ye FU")
def okk():
    Label(InertialMass,text = 'Please input the Piston Mass m_piston in kg ').grid(row=0,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.pistonmass = Entry(InertialMass)
    InertialMass.pistonmass.grid(row=0,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = 'Your calculated m_piston in Step 3 is (462.94 kg) ').grid(row=0,column= 2,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = 'Please input the piston impact velocity v_impact in m/s').grid(row=5,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.Vimpact = Entry(InertialMass)
    InertialMass.Vimpact.grid(row=5,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = 'Your calculated piston velocity at rupture moment in Step 3 is (241 m/s) ').grid(row=5,column= 2,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = 'Please input the tube strength in MPa ').grid(row=7,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.TubeStrength = Entry(InertialMass)
    InertialMass.TubeStrength.grid(row=7,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = "Please input the tube material Young's modulus in GPa ").grid(row=8,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.YoungM = Entry(InertialMass)
    InertialMass.YoungM.grid(row=8,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = '(Normally 210 GPa for steel) ').grid(row=8,column= 2,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = "Please input the tube material density in kg/m^3 ").grid(row=9,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.Density = Entry(InertialMass)
    InertialMass.Density.grid(row=9,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = '(Normally 8000 kg/m^3 for steel) ').grid(row=9,column= 2,padx=5,pady=5,sticky=NW)
    Button (InertialMass, text= 'Click to calculate the  inertial mass ', command= inertialmass).grid(row=10, column= 0,columnspan = 1,padx=5,pady=20,sticky=E+W)
def inertialmass():
    global pistonmass
    global Vimpact
    global TubeStrength
    global YoungM
    global Voverall
    global TES ##tensile elastic stress unit  MPa/(m/s)
    global Density
    global inertialM
    pistonmass = float(InertialMass.pistonmass.get())
    Vimpact = float(InertialMass.Vimpact.get())
    TubeStrength = float(InertialMass.TubeStrength.get())
    YoungM = float(InertialMass.YoungM.get())
    Density = float(InertialMass.Density.get())
    TES = round(numpy.sqrt(Density * YoungM * 1000000000)/1000000,4)
    Voverall = round(TubeStrength/TES,3)
    inertialM = round((pistonmass * Vimpact)/Voverall,1)
    Label(InertialMass,text = ' The calculated tensile elastic stress caused by impact is (%s MPa/(m/s)) '%TES).grid(row=14,column= 0,columnspan = 3, padx=5,pady=5,sticky=W)
    Label(InertialMass,text = ' The calculated maximum allowable V_overall (departure velocity of piston and tube) by impact is (%s m/s) '%Voverall).grid(row=16,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(InertialMass,text = ' The calculated minimum ratio of m_inertial / m_piston is %s '%round((Vimpact/Voverall),3)).grid(row=17,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(InertialMass,text = ' The calculated minimum inertial mass is (%s kg) '%inertialM).grid(row=18,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
```

5.5 Rough Cost Calculator

5.5.1 Function

This module calculates a rough cost mainly including the following parts:

- Material cost of Compression Tube (without gradual-thick application)
- Material cost of Shock Tube;
- Material cost of Acceleration Tube;
- Material cost of piston;
- Material cost of inertial mass;
- Material cost of rail;

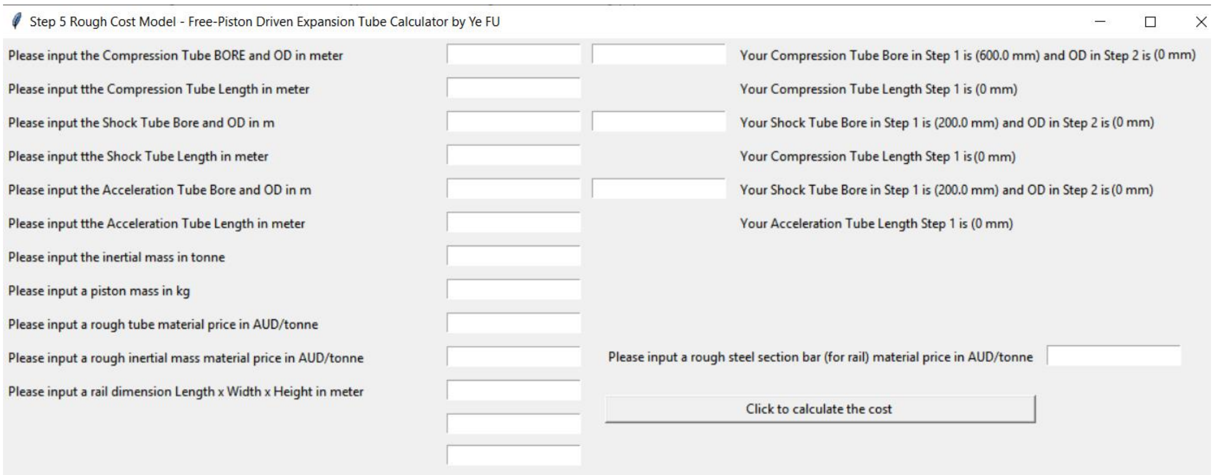


Figure 40. GUI for Step 5 – Cost Model

The processing of raw materials also contributing to the cost significantly. However, as the dramatic price difference and capability between mechanical processers and shops (machining, boring and all other mechanical processing methods).

Other common components contributing to the cost significantly for the construction of an expansion tube facility (not listed in GUI of Figure 40) might include:

- Safety Hardware (e.g. Fire-safety, High-pressure Gas Safety and Hazard Shelter etc…);
- Test Section;
- High-pressure Reservoir;
- Measurement Instrumentations (e.g. dynamical, optical and thermal etc…);
- Hydraulic System and Related Control;
- A lot of standardised mechanical parts (e.g. Flanges, Diaphragms, Bolts and Nuts etc…);
- Tailored parts (e.g. Nozzle, Buffer, Piston-launcher etc…);

- Computing Work Station;
- Gas storage;
- Etc…

5.5.2 Core Code

This section demonstrates partial codes. Please refer to Appendix E for more details.

```
def okk():
  Label(CostModel,text = 'Please input the Compression Tube BORE and OD in meter ').grid(row=0,column=0,padx=5,pady=5,sticky=NW)
  CostModel.CTBore = Entry(CostModel)
  CostModel.CTBore.grid(row=0,column= 1,padx=5,pady=5,sticky=NW)
  CostModel.CTOD = Entry(CostModel)
  CostModel.CTOD.grid(row=0,column= 2,padx=5,pady=5,sticky=NW)
  Label(CostModel,text = 'Your Compression Tube Bore in Step 1 is (%s mm) and OD in Step 2 is (%s mm)'%(float(ETDimension[0]),float(ETOD[0]))).grid(row=0,column= 3,padx=5,pady=5,sticky=NW)
  Label(CostModel,text = 'Please input tthe Compression Tube Length in meter').grid(row=1,column= 0,padx=5,pady=5,sticky=NW)
  CostModel.CTL = Entry(CostModel)
  CostModel.CTL.grid(row=1,column= 1,padx=5,pady=5,sticky=NW)
  Label(CostModel,text = 'Your Compression Tube Length Step 1 is (%s mm) '%(float(ETDimension[3]))).grid(row=1,column= 3,padx=5,pady=5,sticky=NW)
  Label(CostModel,text = 'Please input the Shock Tube Bore and OD in m ').grid(row=2,column= 0,padx=5,pady=5,sticky=NW)
  CostModel.STBore = Entry(CostModel)
  CostModel.STBore.grid(row=2,column= 1,padx=5,pady=5,sticky=NW)
  CostModel.STOD = Entry(CostModel)
  CostModel.STOD.grid(row=2,column= 2,padx=5,pady=5,sticky=NW)
  Label(CostModel,text = 'Your Shock Tube Bore in Step 1 is (%s mm) and OD in Step 2 is (%s mm)'%(float(ETDimension[1]),float(ETOD[1]))).grid(row=2,column= 3,padx=5,pady=5,sticky=NW)
  ...WIDGETS...
def okCost():
  SteelDensity = 8 #tonne/m^3
  CTBore = float(CostModel.CTBore.get())
  CTOD = float(CostModel.CTOD.get())
  CTL = float(CostModel.CTL.get())
  STBore = float(CostModel.STBore.get())
  STOD = float(CostModel.STOD.get())
  STL = float(CostModel.STL.get())
  ATBore = float(CostModel.ATBore.get())
  ATOD = float(CostModel.ATOD.get())
  ATL = float(CostModel.ATL.get())
  InertialMass = float(CostModel.InertialMass.get())
  PistonMass_tonne = float(CostModel.PistonMass.get())/1000
  TubePrice = float(CostModel.TubePrice.get())
  MassPrice = float(CostModel.MassPrice.get())
  RailLength = float(CostModel.RailLength.get())
  RailWidth = float(CostModel.RailWidth.get())
  RailHeight = float(CostModel.RailHeight.get())
  RailPrice = float(CostModel.RailPrice.get())
  CTCost = round(numpy.pi* (CTOD*CTOD - CTBore*CTBore) *CTL* SteelDensity * TubePrice,4)
  STCost = round(numpy.pi*(STOD*STOD - STBore*STBore)*STL* SteelDensity * TubePrice,4)
  ATCost = round(numpy.pi*(ATOD*ATOD - ATBore*ATBore)*ATL* SteelDensity * TubePrice,4)
  TubeCost =round(CTCost+ATCost+STCost,2)
  MassCost = round((InertialMass + PistonMass_tonne)* MassPrice,2)
  RailCost = round(RailLength*RailWidth*RailHeight*RailPrice*SteelDensity,2)
  OverallCost = round(TubeCost + MassCost+RailCost,2)
  ...GUIs...
```

Chapter 6 Case Study 1 - Delivery One Set of Design

This chapter presents a case study to deliver one set of design using the Free-piston Expansion Tube Calculator illustrated in Chapter 5 . This case study can also be regarded as the tutorial about how to use this tool to assist the user performing a preliminary design.

6.1 Step 1 – Dimension

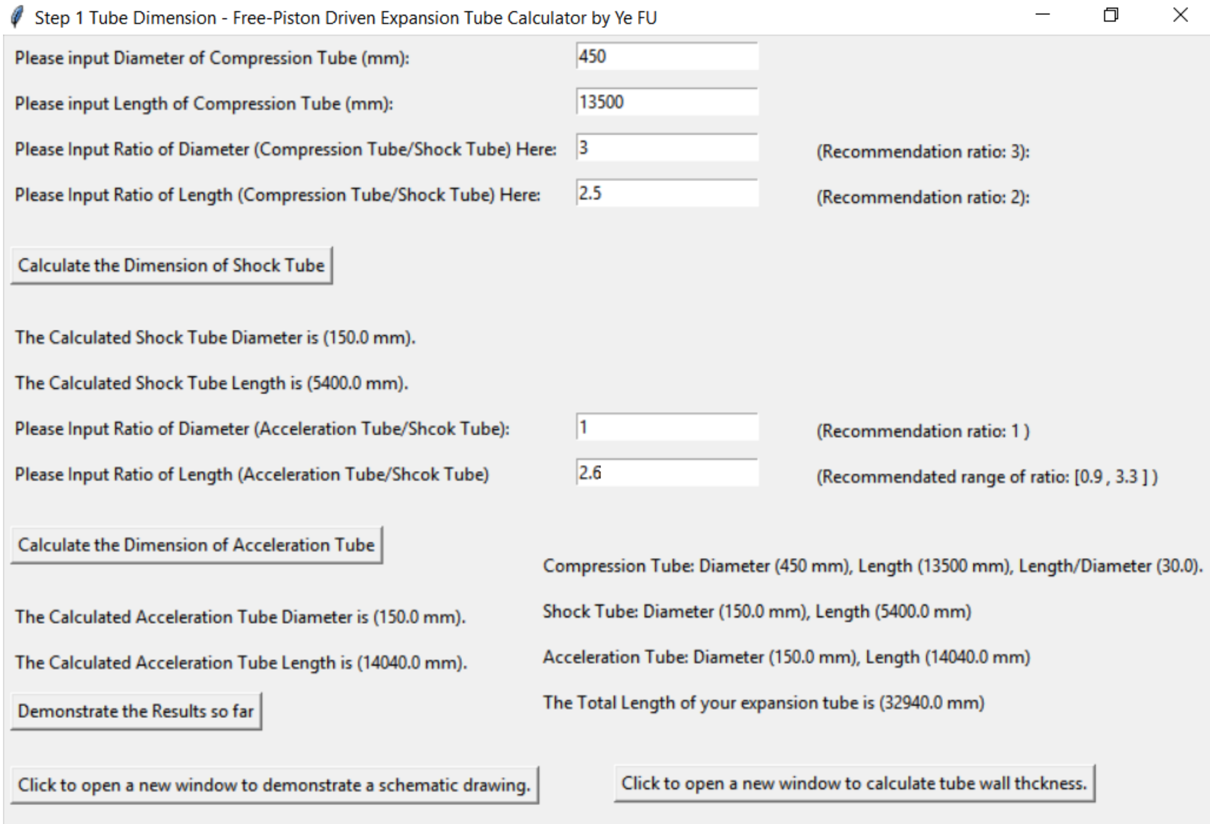


Figure 41. Calculation of Dimension in Step 1

Please note that the tube diameter in Step 1 refers to the bore parameter, which is the effective inner flow field dimension. Figure 41above demonstrates the calculation results of dimension results for this case study, which is summarised in the table below:

Table 12. Summary of dimension for this run

	Dimension	
	Compression Tube	Shock Tube
Length (mm)	13,500	5,400
Diameter (mm)	450	150
	Ratio	
L_CT/D_CT	L_CT/L_ST	L_AT/L_ST
30	2.5	2.6

6.2 Step 2 Tube Wall Thickness Calculation

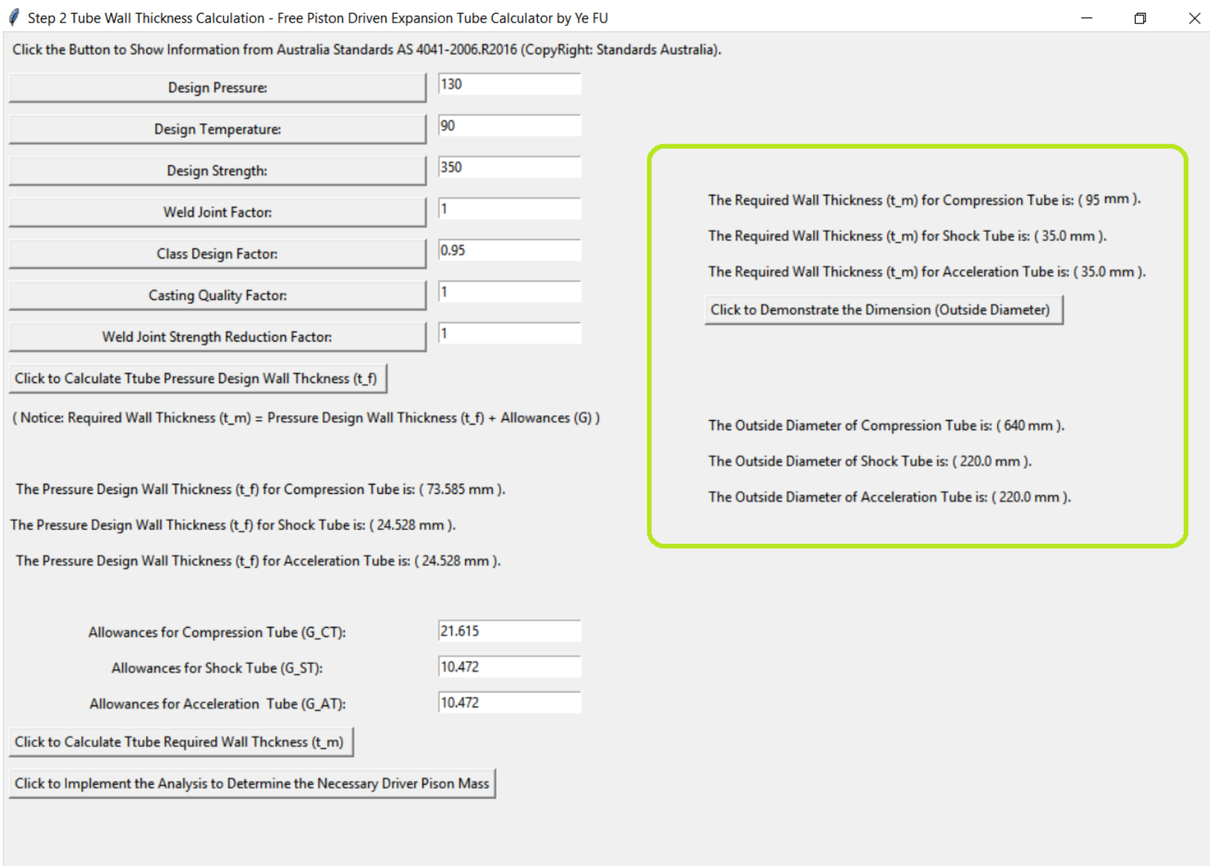


Figure 42. Calculation of Wall Thickness in Step 2 (results highlighted)

The inputted parameters are:

- Design pressure: 130 MPa;
- Design temperature: 90 deg.C;
- Design strength: 350 MPa;
- Class Design Factor 0.95 and all other factors: 1.

The highlighted area in the window of Figure 42summarises the calculation results of Step 2. As we have known, the diameter in Step 1 refers to the bore. The actual tube outside diameters and related wall thickness are summarised in the Table 15 below.

Table 13. Tube wall thickness calculation results

	Dimension		
	Compression Tube	Shock Tube	Acceleration Tube
Length (mm)	13,500	5,400	14,040
Diameter (mm)	450	150	150
	Wall Thickness		
	Compression Tube	Shock Tube	Acceleration Tube

Design Thickness (mm)	73.385	24.528	24.528
Allowances (mm)	21.615	10.472	10.472
Required Thickness (mm)	95	35	35
Outside Diameter (mm)	640	220	220

6.3 Step 3 – Calculation of Necessary Piston Mass

6.3.1 Piston Mass Calculation Test Run 1

The determination of piston mass is very open-minded in Step 3. If the user has a flow condition in mind, a related piston mass can be calculated. Figure below is a configured screen shot showing a calculated necessary piston mass of 130.65 kg under this condition:

- Compression ratio: 50;
- Length between piston front face to compression tube end wall: 13500 mm;
- Desired primary diaphragm rupture pressure: 50 MPa;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);
- Driver filling pressure: 10 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Desired tested Reservoir Filling Pressure: 15 MPa.

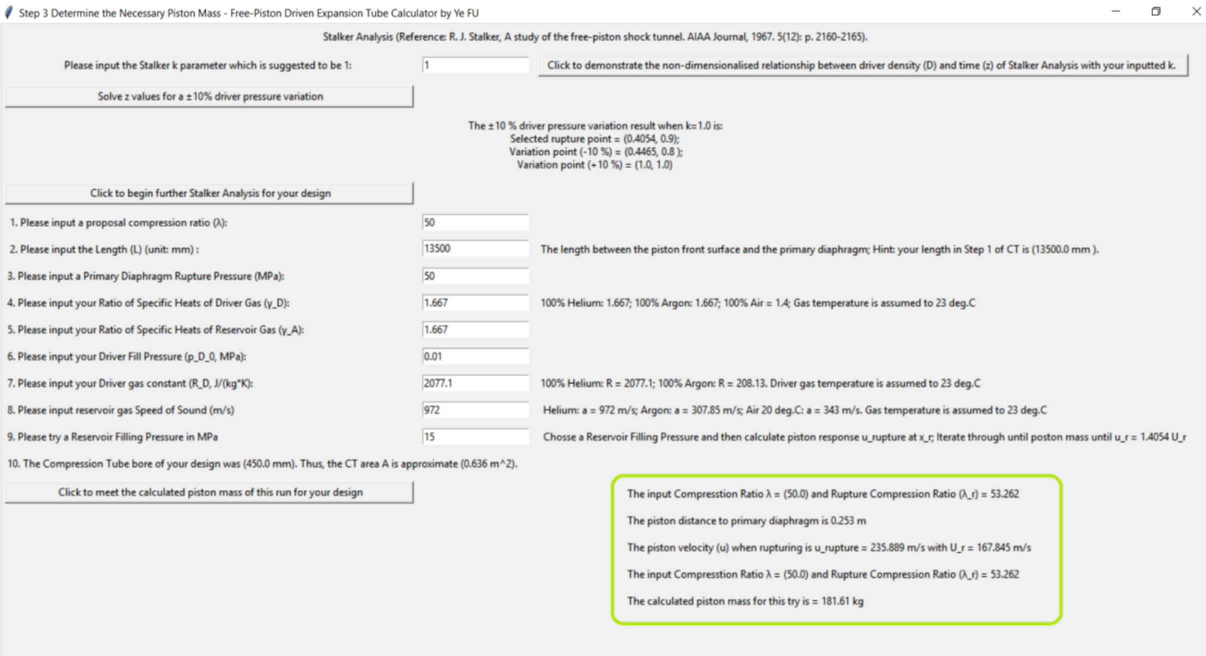


Figure 43. Demonstration of calculated results (highlighted area) (GUI configured)

After iterating until $u_{rupture}$ = 1.4054 U_r, the calculated results under this condition are:

- Rupture compression ratio: 53.262;
- Piston face to CT-ST throat entry: 0.253 m;

- **Calculated necessary piston mass**: 181.61 kg.

6.4 Step 4 – Calculation of Inertial Mass

6.4.1 Inertial Mass Calculation Test Run 1

This test run uses the results from previous section which are summarised below:

- Piston mass: 181.61 kg;
- Assumed impact velocity: 236 m/s;
- Tube strength: 350 MPa;

The calculated results demonstrated in are summarised below:

- Stress by impact: Extra 41.1157 MPa for every 1 m/s increase on departure velocity;
- Minimum inertial mass for a 130.65 kg piston: 5020.5 kg.

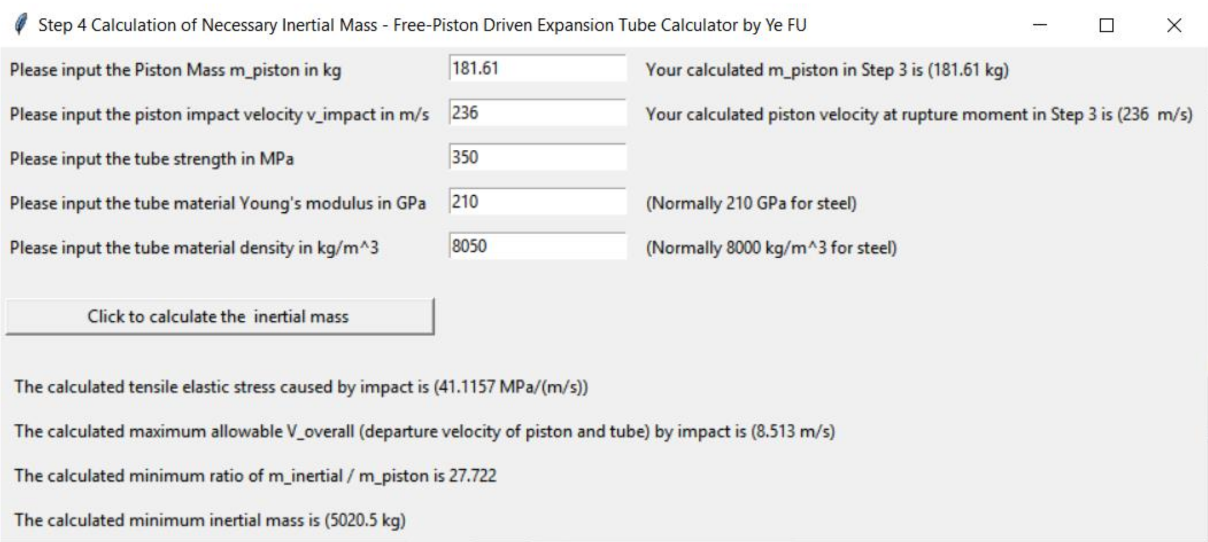


Figure 44. Calculated inertial mass using results

6.5 Rough Cost Model

6.5.1 Raw Material Cost

This section calculates a rough raw material cost for this set of design.

From one of the steel hollow bar catalogues, for the shock tube and acceleration tube sections with design parameter (OD×ID = 220 mm × 150 mm), the raw material supply dimension would be (OD×ID = 236 mm × 149 mm) with unit weight of 233 kg/m. Thus, for a 5.4-meter long shock tube and an 15-meter long shock tube, the overall demand length of hollow bar is 22 meters, which is 5,126 kilograms (rounding to 5.2 tonnes).

For the compression tube design parameter (OD×ID = 640 mm × 450 mm), the raw material supply dimension would be (OD×ID = 660 mm × 500 mm) with unit weight of 1165 kg/m. Thus, for a 13.5-meter long compression tube, the overall demand weight of hollow bar is 15727.5 kilograms. As the previous chapter mentioned, the compression tube can be constructed using the extendable and gradual-thick methodology, the overall demand weight can be rounded to 16 tonnes.

The required inertial mass will be used to calculate the cost of this case (the chapter 7.4.3 result), 13105 kilograms to a 462.94, which means almost 13 tonnes inertial mass are required for launching a 460-kg scale piston. As X4 aims to be human-scale operational, the piston mass has a great possibility not to reach over 200 kilograms (even above 100 kilograms). Thus, using this 13-ton inertial mass for a 460-kg scale piston can provide a margin of design safety.

6.5.2 Processing

The material processing cost is not included within this calculation results.

6.5.3 Results from the Program

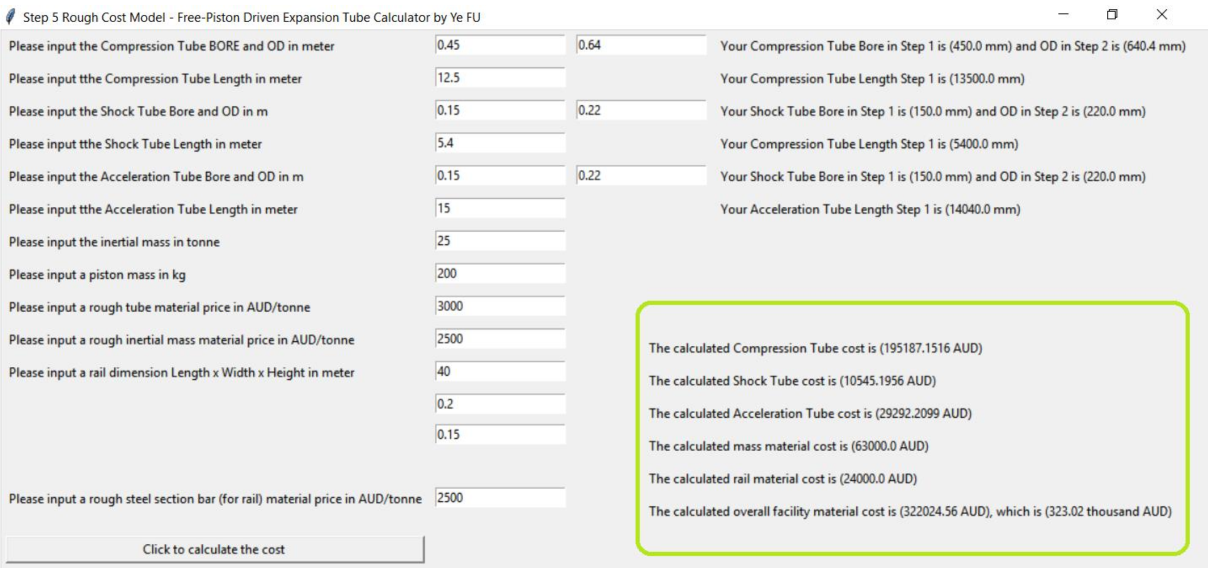


Figure 45. Rough cost model for this case model (raw material directed)

The calculation prices are (might be higher than the real market prices):

- Mass material: 2500 AUD/tonne;
- Tube: 3000 AUD/tonne;
- Rail: 2500 AUD/tonne.

As is demonstrated in the Figure 45, the calculated results of raw material cost are summarised below:

- Compression Tube (without gradual-thick optimisation): Almost 200 thousand AUD;
- Shock Tube cost: Almost 3 thousand AUD: Almost 11 thousand AUD;
- Acceleration Tube cost: Almost 30 thousand AUD;
- Inertial and piston mass cost: Almost 63 thousand AUD;
- Rail cost: Almost 24 thousand AUD;
- Sum-up: Almost 323 thousand AUD.

Please note that this cost is far away from the real construction cost because material processing and several facility components are not included:

- Safety Hardware (e.g. Fire-safety, High-pressure Gas Safety and Hazard Shelter etc…);
- Test Section;
- High-pressure Reservoir;
- Measurement Instrumentations (e.g. dynamical, optical and thermal etc…);
- Hydraulic System and Related Control;
- A lot of standardised mechanical parts (e.g. Flanges, Diaphragms, Bolts and Nuts etc…);
- Tailored parts (e.g. Nozzle, Buffer, Piston-launcher etc…);
- Computing Work Station;
- Gas storage;
- A lot of other costly things.

Chapter 7 Case Study 2 – Deliver a Larger-scale Design

Unlike Case Study 1 in Chapter 6 this case study performs a design of a large-scale facility

This chapter presents another case study to deliver another set of design unlike the design of a medium-sized expansion tube facility in Chapter 6 . This case study aims to demonstrate a design approaching the upper range (60-meter scale) for given guidelines of design range in Chapter 4

The design tool is still used, which is the Free-piston Expansion Tube Calculator illustrated in Chapter 5 .

7.1 Step 1 – Dimension

The compression tube bore range was guided to be from 330 to 620 mm in section 4.3, so this run uses 600 mm bore diameter for compression tube to perform the following case study.

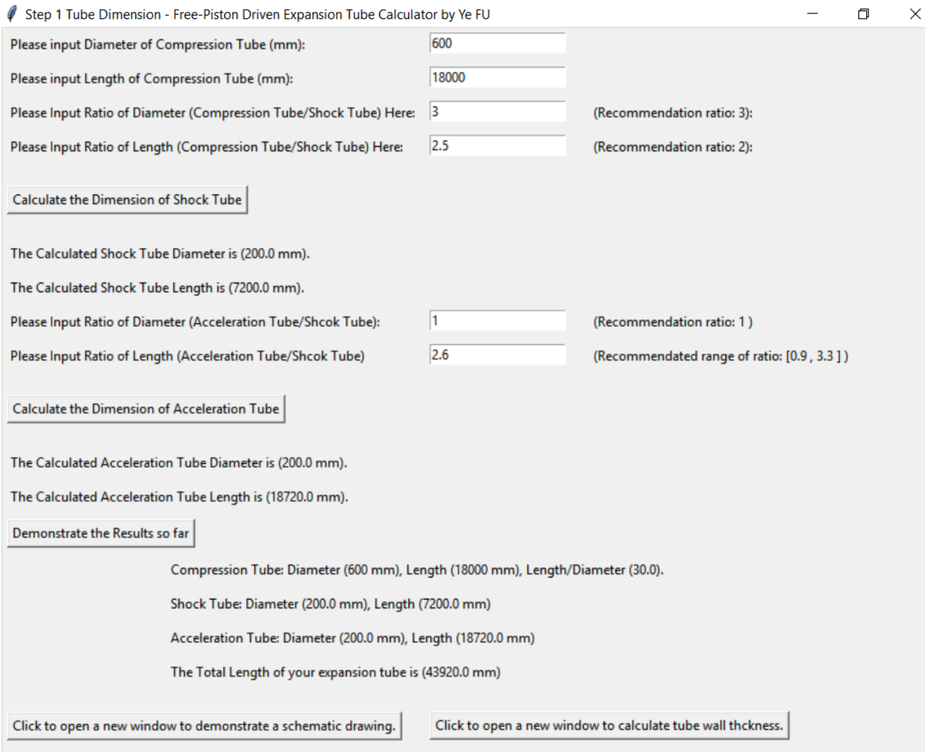


Figure 46. Calculation of Dimension in Step 1

Please note that the tube diameter in Step 1 refers to the bore parameter, which is the effective inner flow field dimension. For this run, the compression tube initial length was set to be 18000 mm, which caused a 43920 mm total length without test section and other facility components considered. From the operation experiences, the final length might be around 60000 mm with other sections accounted.

Figure 46 above demonstrates the calculation results of dimension results for this case study, which is summarised in the Table 14 below:

Table 14. Summary of dimension for this run

Dimension			
	Compression Tube	Shock Tube	Acceleration Tube
Length (mm)	18,000	9,000	18,720
Diameter (mm)	600	200	200
Ratio			
L_CT/D_CT	L_CT/L_ST	L_AT/L_ST	D_CT/D_ST
30	2.5	2.6	3

7.2 Step 2 Tube Wall Thickness Calculation

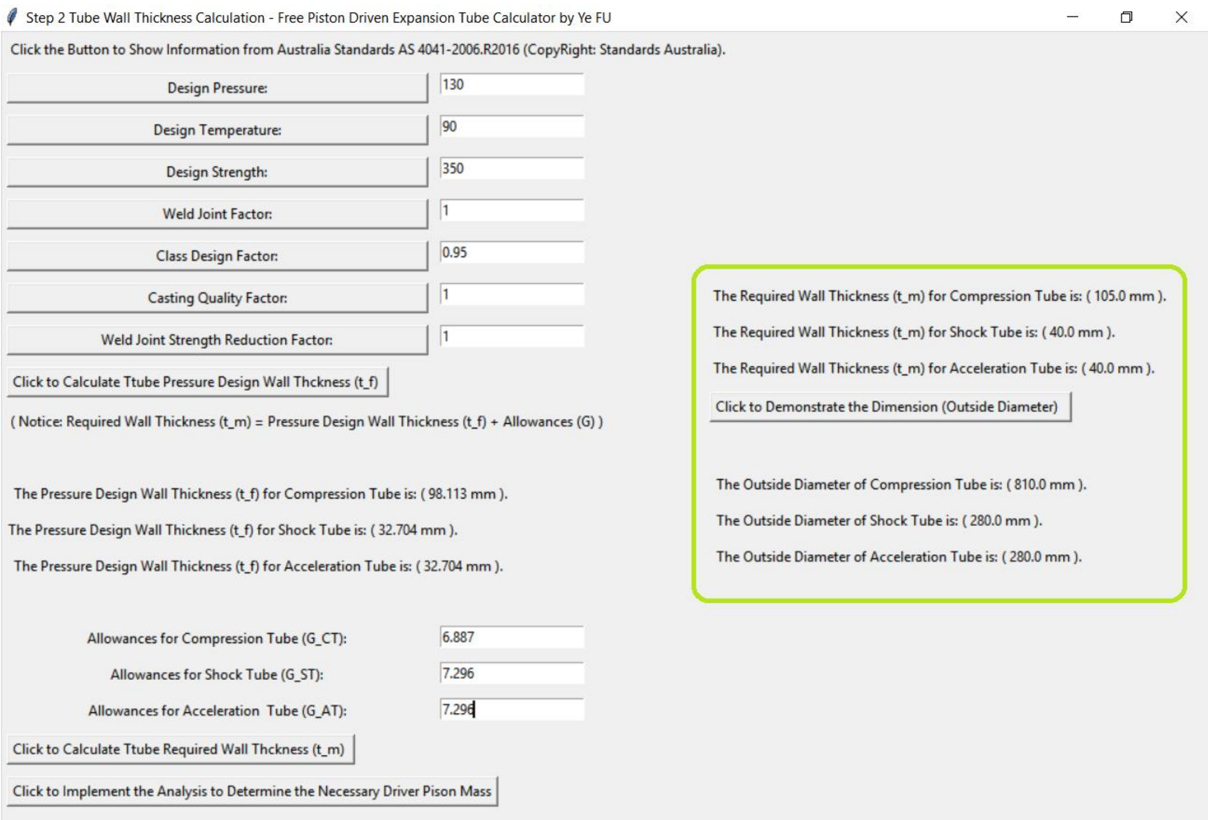


Figure 47. Calculation of Wall Thickness in Step 2 (results highlighted)

The inputted parameters are:

- Design pressure: 130 MPa;
- Design temperature: 90 deg.C;
- Design strength: 350 MPa;
- Class Design Factor: 0.95;
- Other factors: 1.

The highlighted area in the window of Figure 47 summarises the calculation results of Step 2. As we have known, the diameter in Step 1 refers to the bore. The actual tube outside diameters and related wall thickness are summarised in the Table 15 below.

Table 15. Tube wall thickness calculation results

	Dimension		
	Compression Tube	Shock Tube	Acceleration Tube
Length (mm)	18,000	9,000	18,720
Diameter (mm)	600	200	200
	Wall Thickness		
	Compression Tube	Shock Tube	Acceleration Tube
Design Thickness (mm)	98.113	32.704	32.704
Allowances (mm)	6.887	7.296	7.296
Required Thickness (mm)	105	40	40
Outside Diameter (mm)	810	280	280

7.3 Step 3 – Calculation of Necessary Piston Mass

7.3.1 Piston Mass Calculation Test Run 1

The determination of piston mass is very open-minded in Step 3. If the user has a flow condition in mind, a related piston mass can be calculated. Figure 48 below is a configured screen shot showing a calculated necessary piston mass of 130.65 kg under this condition:

- Compression ratio: 40;
- Length between piston front face to compression tube end wall: 18000 mm;
- Desired primary diaphragm rupture pressure: 30 MPa;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);
- Driver filling pressure: 1 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Desired tested Reservoir Filling Pressure: 15 MPa.

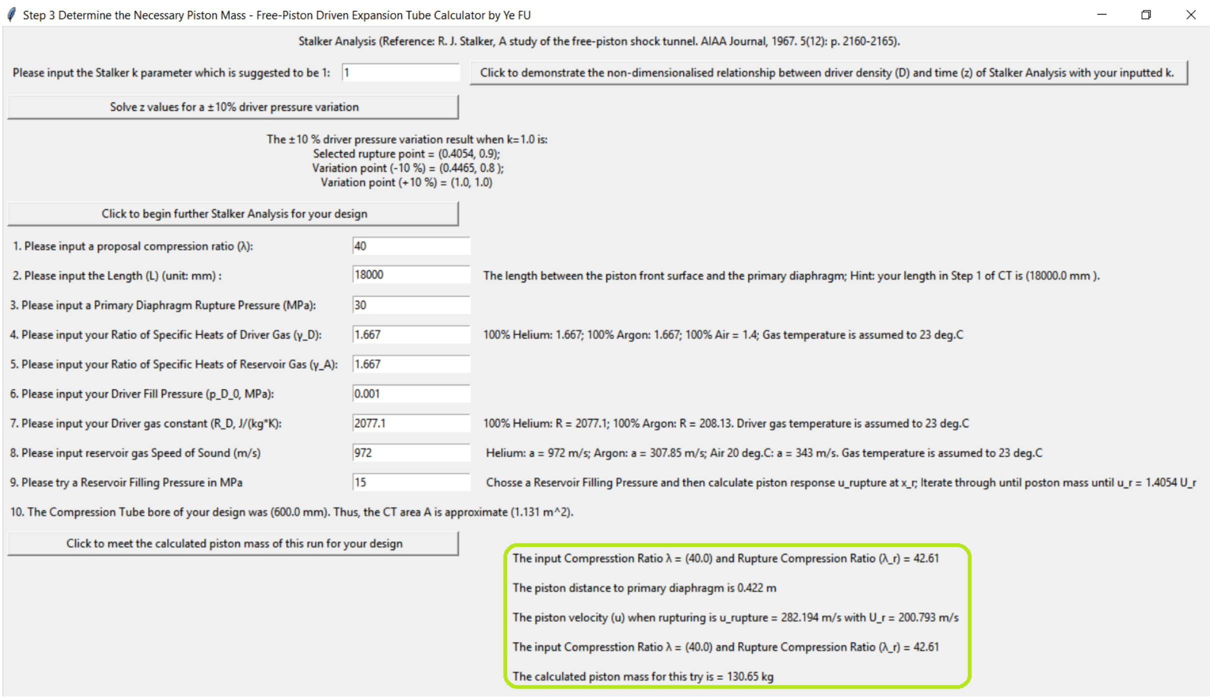


Figure 48. Demonstration of calculated results (highlighted area) (GUI configured)

After iterating until $u_{rupture}$ = 1.4054 U_r, the calculated results under this condition are:

- Rupture compression ratio: 42.61;
- Piston face to CT-ST throat entry: 0.422 m;
- **Calculated necessary piston mass**: 130.65 kg.

7.3.2 Piston Mass Calculation Test Run 2

Figure 49 below is a configured screen shot showing a calculated necessary piston mass of 234.29 kg under this condition:

- Compression ratio: 50;
- Length between piston front face to compression tube end wall: 16000 mm;
- Desired primary diaphragm rupture pressure: 50 MPa;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);
- Driver filling pressure: 1 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Desired tested Reservoir Filling Pressure: 15 MPa.

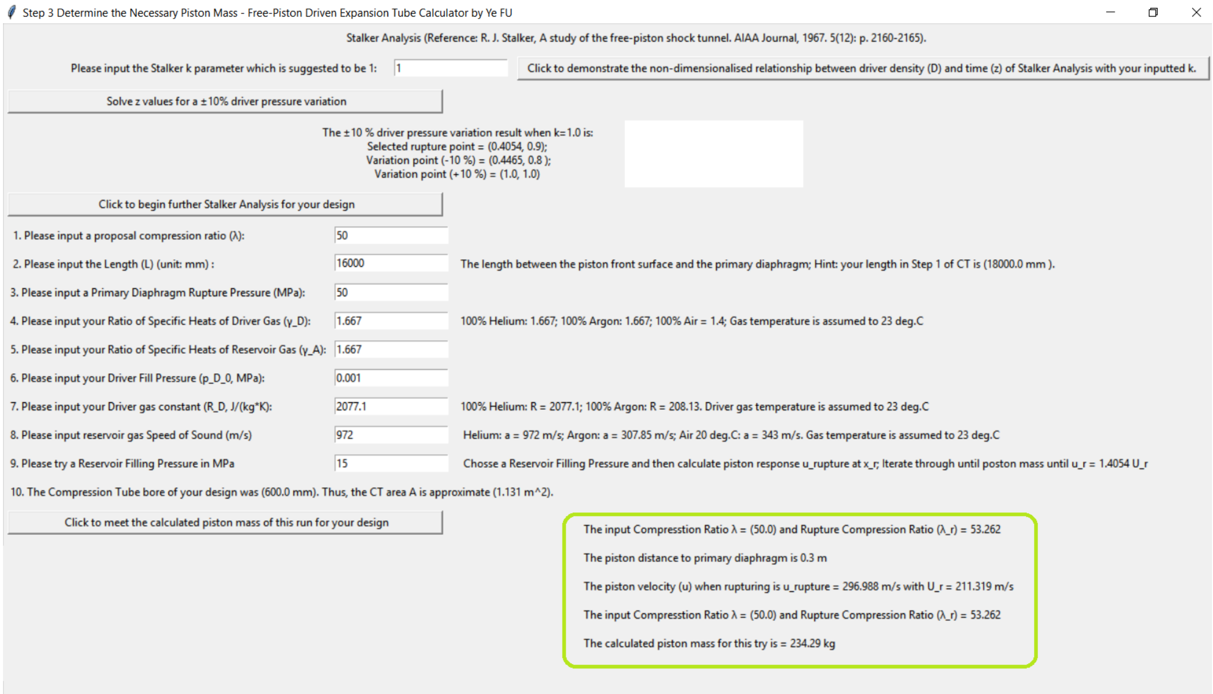


Figure 49. Demonstration of calculated results (highlighted area) (GUI configured)

After iterating until $u_{rupture}$ = 1.4054 U_r, the calculated results under this condition are:

- Rupture compression ratio: 53.262;
- Piston face to CT-ST throat entry: 0.3 m;
- **Calculated necessary piston mass**: 234.29 kg.

7.3.3 Piston Mass Calculation Test Run 3

Figure 49 below is a configured screen shot showing a calculated necessary piston mass of 234.29 kg under this condition:

- Compression ratio: 60;
- Length between piston front face to compression tube end wall: 16000 mm;
- Desired primary diaphragm rupture pressure: 60 MPa;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);
- Driver filling pressure: 1 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Desired tested Reservoir Filling Pressure: 10 MPa.

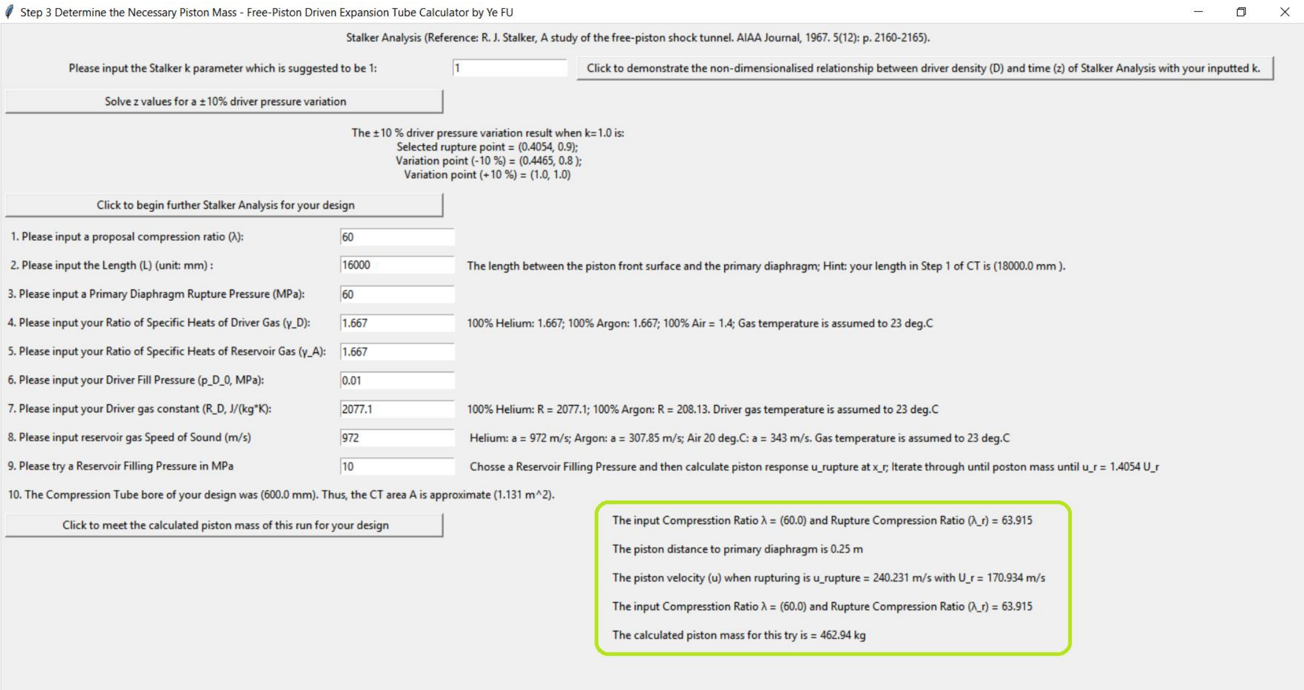


Figure 50. Demonstration of calculated results (highlighted area) (GUI configured)

After iterating until $u_{rupture}$ = 1.4054 U_r, the calculated results under this condition are:

- Rupture compression ratio: 63.915;
- Piston face to CT-ST throat entry: 0.25 m;
- **Calculated necessary piston mass**: 462.94 kg.

7.4 Step 4 – Calculation of Inertial Mass

7.4.1 Inertial Mass Calculation Test Run 1

This test run uses the results from section 7.3.1 which are summarised below:

- Piston mass: 130.65 kg;
- Assumed impact velocity: 282.194 m/s;
- Tube strength: 350 MPa;

The calculated results demonstrated in are summarised below:

- Stress by impact: Extra 41.1157 MPa for every 1 m/s increase on departure velocity;
- Minimum inertial mass for a 130.65 kg piston: 4330.9 kg.

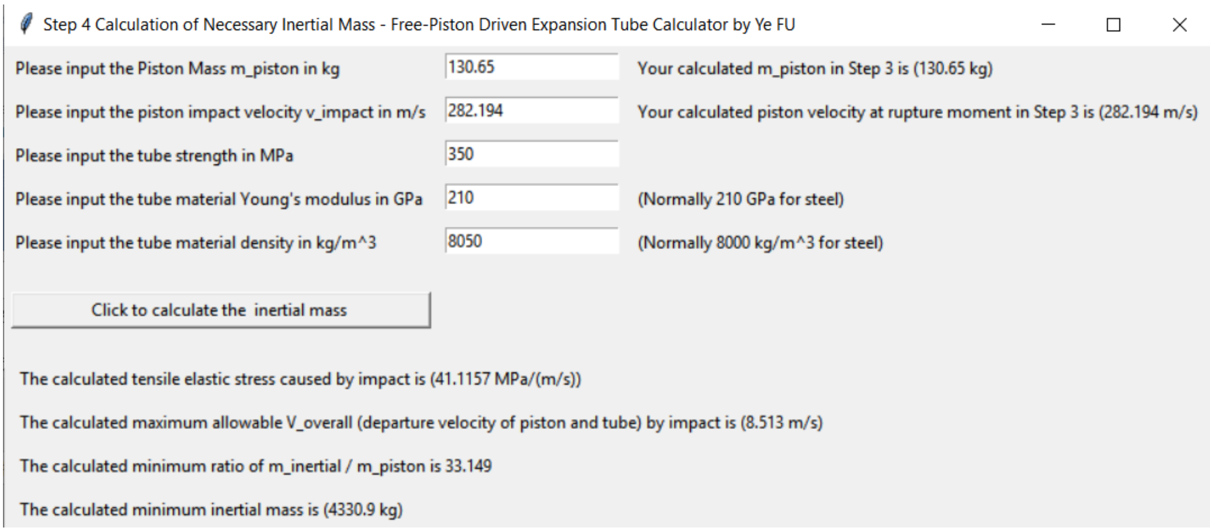


Figure 51. Calculated inertial mass using results from section 7.3.1

7.4.2 Inertial Mass Calculation Test Run 2

This test run uses the results from section 7.3.2 which are summarised below:

- Piston mass: 234.29 kg;
- Assumed impact velocity: 297 m/s;
- Tube strength: 350 MPa;

The calculated results demonstrated in Figure 52 are summarised below:

- Stress by impact: Extra 41.1157 MPa for every 1 m/s increase on departure velocity;
- Minimum inertial mass for a 130.65 kg piston: 8173.9 kg.

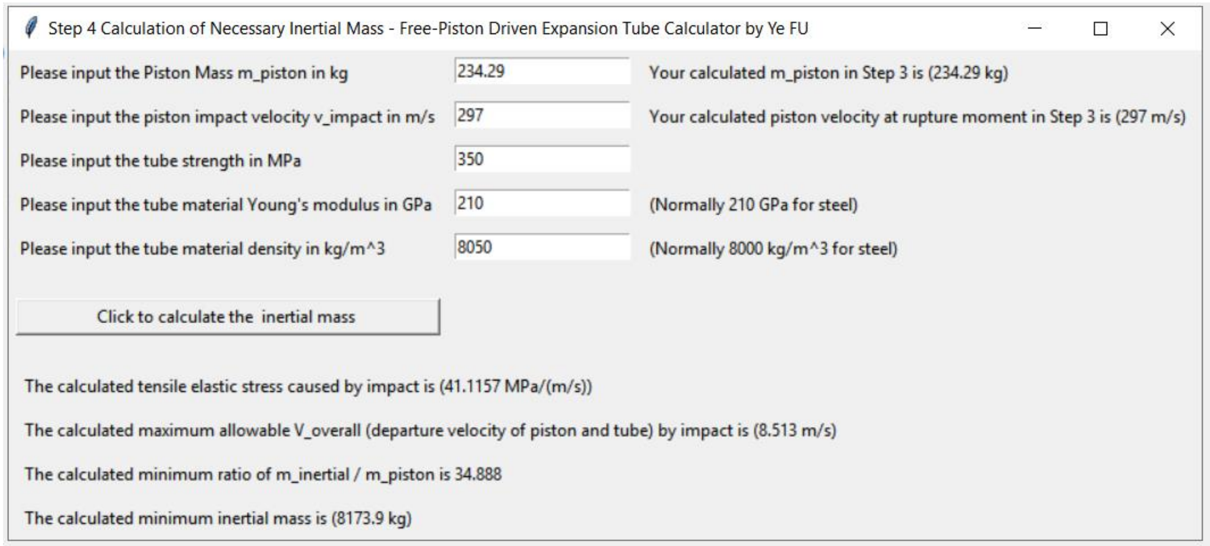


Figure 52. Calculated inertial mass using results from section 7.3.2

7.4.3 Inertial Mass Calculation Test Run 3

This test run uses the results from section 7.3.3 which are summarised below:

- Piston mass: 462.94 kg;
- Assumed impact velocity: 241 m/s;
- Tube strength: 350 MPa;

The calculated results demonstrated in Figure 53 are summarised below:

- Stress by impact: Extra 41.1157 MPa for every 1 m/s increase on departure velocity;
- Minimum inertial mass for a 462.94 kg piston: 13105.7 kg.

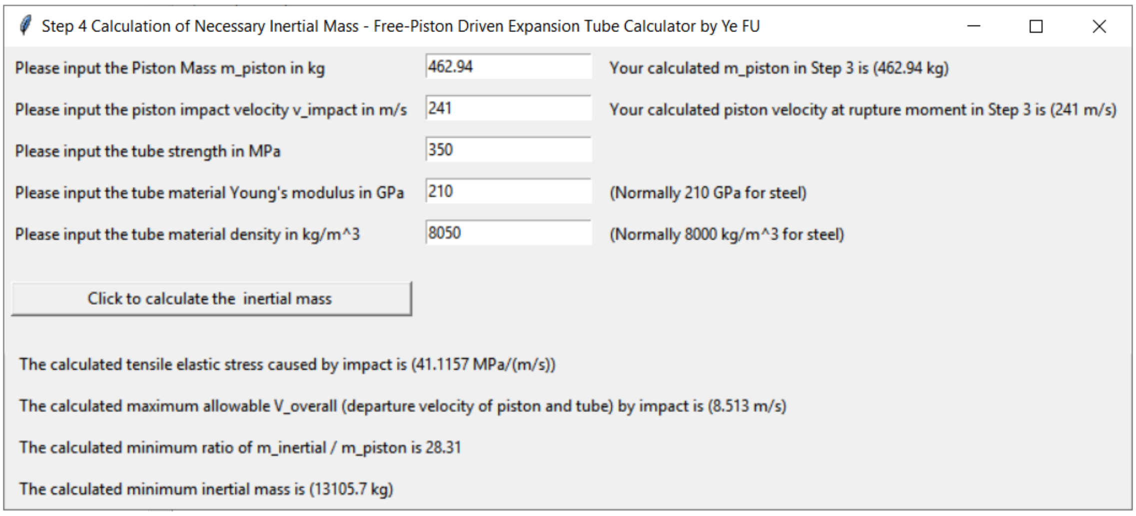


Figure 53. Calculated inertial mass using results from section 7.3.3

7.5 Rough Cost Model

7.5.1 Raw Material Cost

This section calculates a rough raw material cost for this set of design.

From one of the steel hollow bar catalogues, for the shock tube and acceleration tube sections with design parameter (OD×ID = 280 mm × 200 mm), the raw material supply dimension would be (OD×ID = 298 mm × 198 mm) [40]with unit weight of 306.41 kg/m. Thus, for a 7.2-meter long shock tube and an 18.72-meter long shock tube, the overall demand length of hollow bar is 26 meters, which is 7966.66 kilograms (rounding to 8 tonnes).

For the compression tube design parameter (OD×ID = 810 mm × 600 mm), the raw material supply dimension would be (OD×ID = 812 mm × 617 mm) with unit weight of 1749 kg/m. Thus, for a 18-meter long compression tube, the overall demand weight of hollow bar is 31482 kilograms. As the previous chapter mentioned, the compression tube can be constructed using the extendable and gradual-thick methodology, the overall demand weight can be rounded to 30 tonnes.

The required inertial mass will be used to calculate the cost of this case (the chapter 7.4.3 result), 13105 kilograms to a 462.94, which means almost 13 tonnes inertial mass are required for launching a 460-kg scale piston. As X4 aims to be human-scale operational, the piston mass has a great possibility not to reach over 200 kilograms (even above 100 kilograms). Thus, using this 13-ton inertial mass for a 460-kg scale piston can provide a margin of design safety.

7.5.2 Processing

The processing cost is not included within this calculation results.

7.5.3 Results from the Program

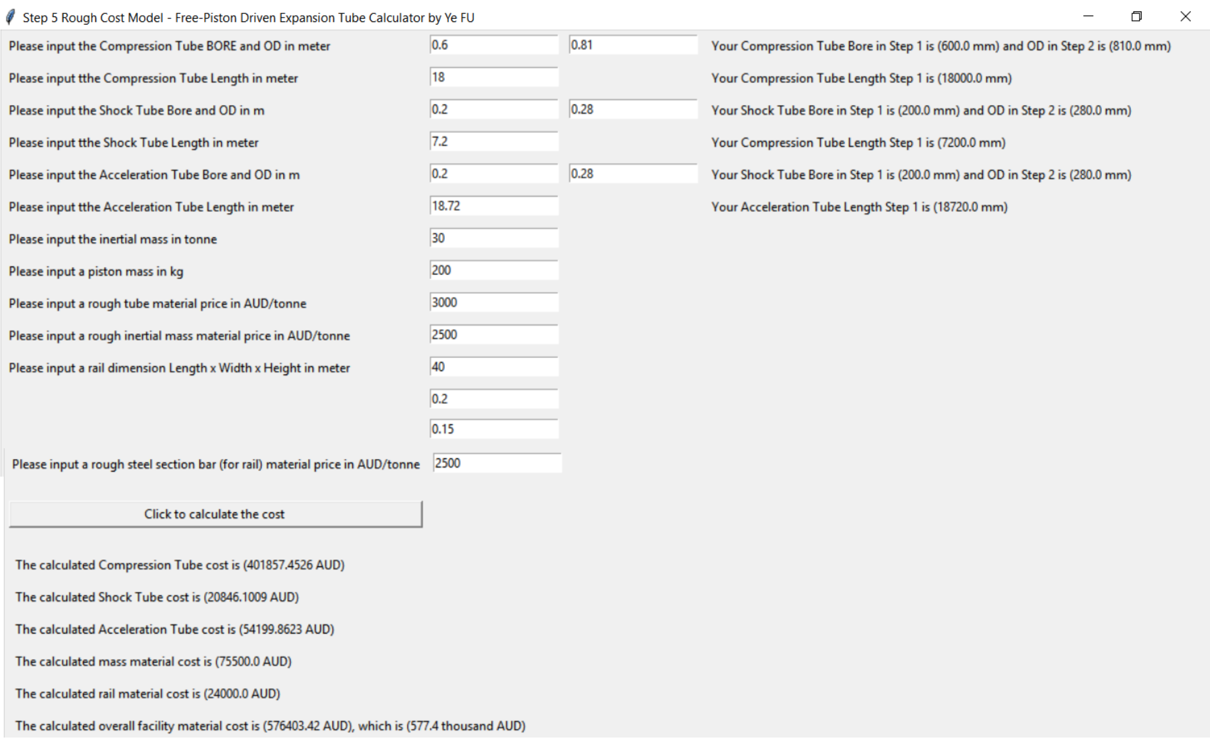


Figure 54. Rough cost model for this case model (raw material directed)

The calculation unit prices are (might be higher than the real market prices):

- Mass material: 2500 AUD/tonne;
- Tube: 3000 AUD/tonne;
- Rail: 2500 AUD/tonne.

As is demonstrated in the Figure 54, the calculated results of raw material cost are summarised below:

- Compression Tube cost (without gradual-thick optimisation): Almost 401 thousand AUD;
- Shock Tube cost: Almost 3 thousand AUD: Almost 20 thousand AUD;
- Acceleration Tube cost: Almost 55 thousand AUD;
- Inertial and piston mass cost: Almost 76 thousand AUD;
- Rail cost: Almost 24 thousand AUD;
- Sum-up: Almost 578 thousand AUD.

Please note that this cost is far away from the real construction cost because material processing and several facility components are not included:

- Safety Hardware (e.g. Fire-safety, High-pressure Gas Safety and Hazard Shelter etc…);
- Test Section;
- High-pressure Reservoir;
- Measurement Instrumentations (e.g. dynamical, optical and thermal etc…);
- Hydraulic System and Related Control;
- A lot of standardised mechanical parts (e.g. Flanges, Diaphragms, Bolts and Nuts etc…);
- Tailored parts (e.g. Nozzle, Buffer, Piston-launcher etc…);
- Computing Work Station;
- Gas storage;
- A lot of other costly things.

Chapter 8 Case Study 3 – A Study of Driver Filling Pressure

8.1 Aim

This case aims to study the variation of permitted driver piston mass range as the driver filling pressure changes. Operation experiences of free-piston driver indicate that the driver gas pressure cannot be too low otherwise the supply of driver gas will be insufficient after primary diaphragm rupture. However, relatively lower driver pressure does help to operate a lighter piston at higher rupture speed, which would help to improve the duration of constant driver gas supply pressure.

As for how the range of permitted piston mass would be influenced by driver filling pressure range, this section performs a study to investigate.

8.2 Core Analytical Code

This analysis is done by looping the Step 3 of the program introduced in Chapter 5 , the calculated results are collected and used to generate a chart demonstrated in Figure 55. The core code to conduct this task is collected below:

```
CompressionRatio = 50
Length = 16000
Length_m = 16
RupturePressure = 50
RatioSpecificHeatDriver = 1.667
RatioSpecificHeatReservoir = 1.667
SpeedofSound = 972
R_D = 2077.1
ReservoirFillPressure = 10
DriverFillPressure = numpy.arange(1,100,0.01)
T_D_0 = 23 + 273.15
RuptureCompressionRatio = CompressionRatio / 0.9**(1/RatioSpecificHeatDriver)
U_r =(((2/(RatioSpecificHeatDriver+1))**((RatioSpecificHeatDriver+1)/(2*(RatioSpecificHeatDriver-
1))))* 9 * ((RatioSpecificHeatDriver*R_D*T_D_0*(RupturePressure/(DriverFillPressure*1e-
3))**((RatioSpecificHeatDriver-1)/RatioSpecificHeatDriver))**(0.5)))**(0.5)
u_rupture = (1 - 1*(-0.4054))*U_r
PistonMass = (RupturePressure - ReservoirFillPressure* (1- (0.5*RatioSpecificHeatReservoir-
1)*(1.4*U_r/SpeedofSound))**(2*RatioSpecificHeatReservoir/(RatioSpecificHeatReservoir-
1))) * (Length_m*float(ETDimension[0])*float(ETDimension[0])*numpy.pi/RuptureCompressionRatio/U_r/
U_r)
plt.title(' Variation of Required Piston Mass as Driver Filling Pressure Increasing ', font2)
plt.xlabel('Driver Filling Pressure (kPa)', font2)
plt.ylabel('Permitted Maximum Piston Mass (kg)', font2)
plt.plot(DriverFillPressure, PistonMass)
font2 = {'family' : 'Times New Roman','weight' : 'normal','size'  : 22,}
plt.grid(ON)
#plt.legend()
plt.show()
```

8.3 Run 1

8.3.1 Set Condition

To investigate the necessary piston mass as driver filling pressure changes, the calculation condition needs to be set. The parameters for this condition are summarised below:

- Compression ratio: 50;
- Length between piston front face to compression tube end wall: 16000 mm;
- Desired primary diaphragm rupture pressure: 30 MPa;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);
- Driver filling pressure: 1~100 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Initial temperature: 23 deg.C;
- Desired tested Reservoir Filling Pressure: 10 MPa.

8.3.2 Plot

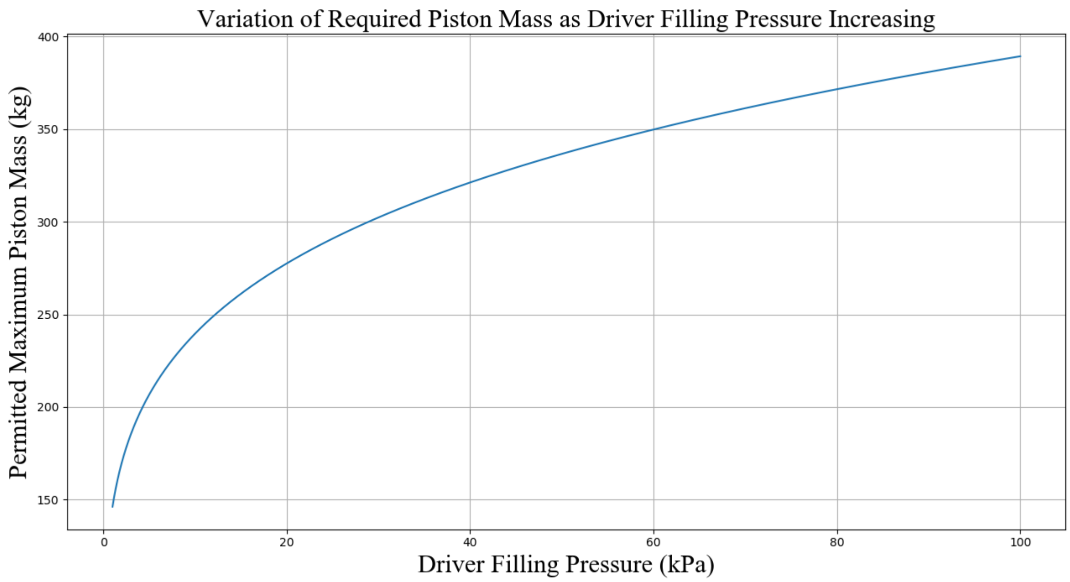


Figure 55. Variation of Required Piston Mass as Driver Filling Pressure Increasing

8.4 Run 2

8.4.1 Set Condition

The parameters for this condition are summarised below with 60 MPa rupture pressure which is 2 times higher than Run 1's 30 MPa:

- Compression ratio: 60;
- Length between piston front face to compression tube end wall: 16000 mm;
- Desired primary diaphragm rupture pressure: 60 MPa;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);
- Driver filling pressure: 1~100 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Initial temperature: 23 deg.C;
- Desired tested Reservoir Filling Pressure: 10 MPa.

8.4.2 Plot

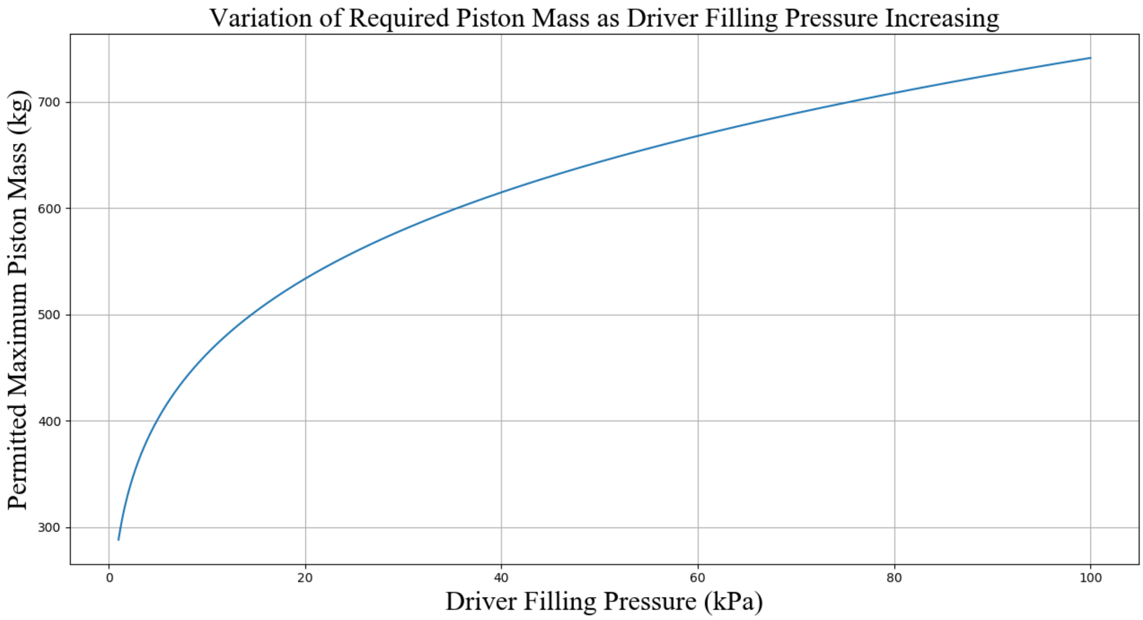


Figure 56. Variation of Piston Mass as Driver Filling Pressure Increasing

8.5 Summary of Results from Multiple Runs

To further investigate dual-variable influence, this section plots results in multiple groups to demonstrate the relationship.

8.5.1 Vary Primary Diaphragm Rupture Pressure

Vary primary diaphragm rupture pressure from 15 to 70 MPa. The summary of results is plotted in Figure 57. This diagram is done by program coded by the author (collected in Appendix Code Collection).

This variation is done under the condition summarised below:

- Compression ratio: 60;
- Length between piston front face to compression tube end wall: 16000 mm;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);

- Driver filling pressure: 1~100 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Initial temperature: 23 deg.C;
- Desired tested Reservoir Filling Pressure: 10 MPa.

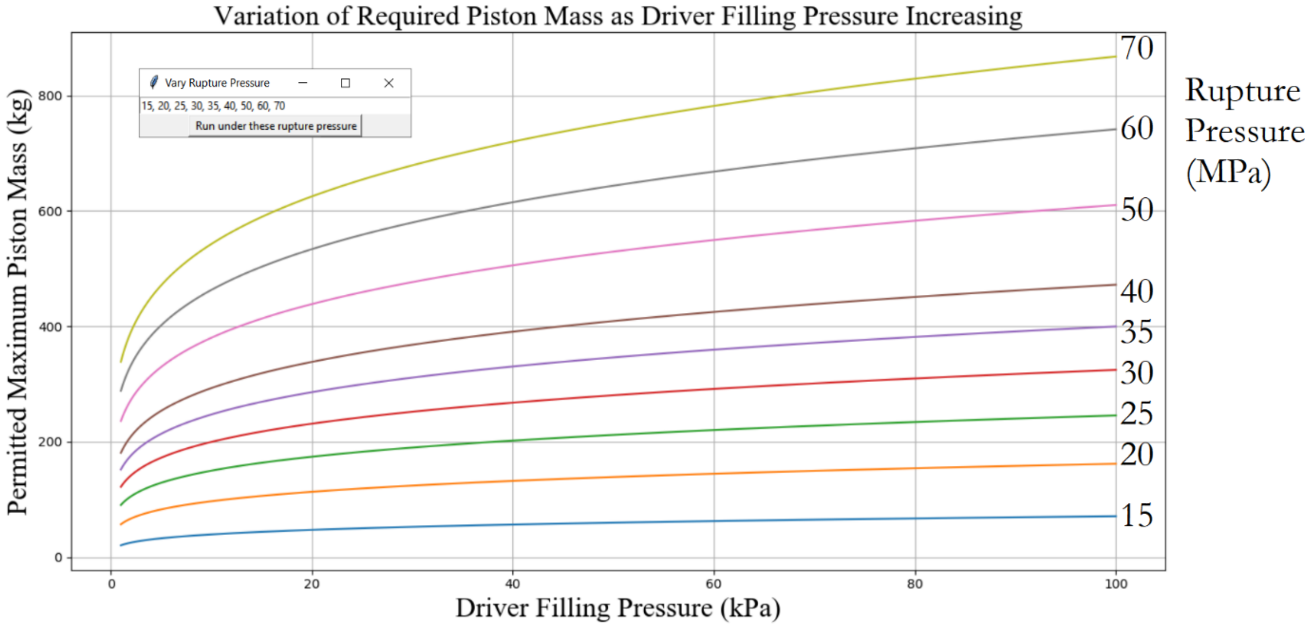


Figure 57. Group plot with Primary Diaphragm Rupture Pressure varied (Relationship of Piston mass versus the initial Driver Filling Pressure)

8.5.2 Vary Compression Ratio

Vary Compression Ratio from 20 to 90 under the condition summarised below:

- Length between piston front face to compression tube end wall: 16000 mm;
- Desired primary diaphragm rupture pressure: 35 MPa;
- Driver gas ratio of specific heats: 1.667 (100% Helium);
- Reservoir gas ratio of specific heats: 1.667 (100% Helium);
- Driver filling pressure: 1~100 kPa;
- Driver gas constant: 2077.1 J/(kg*K) (100% Helium);
- Reservoir gas speed of sound: 972 m/s;
- Initial temperature: 23 deg.C;
- Desired tested Reservoir Filling Pressure: 10 MPa.

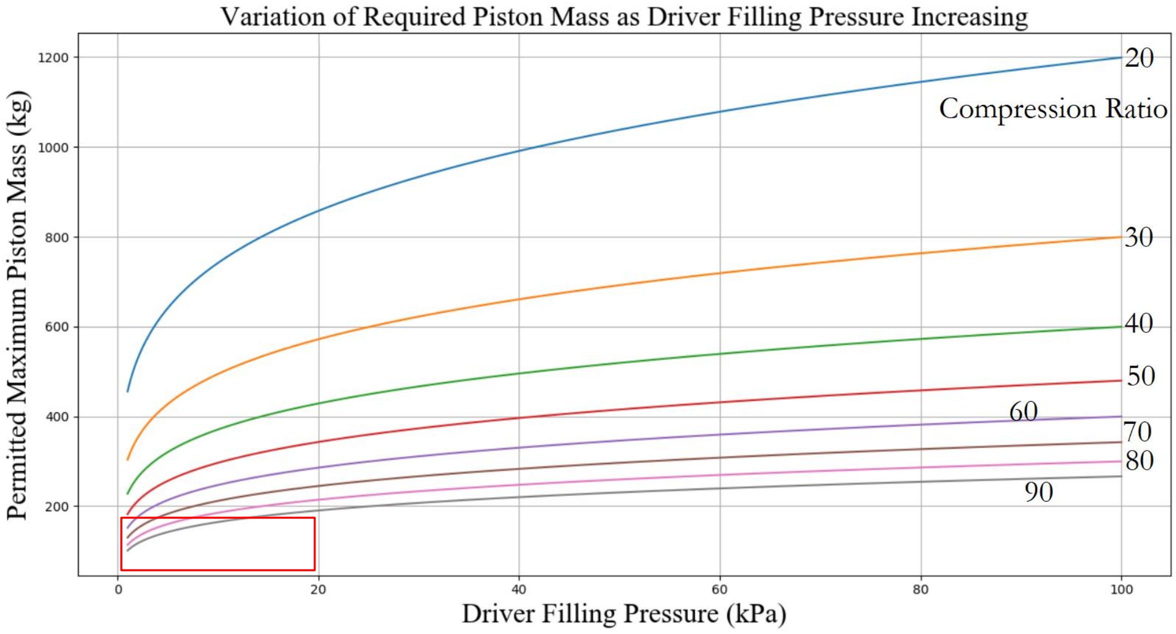


Figure 58. Group plot with Rupture Pressure varied (Piston mass – Driver Filling Pressure)

Under the assumed condition, as compression ratio increasing, the necessary piston mass increases. Compression ratio 20 seems unfeasible for this condition.

8.6 A Qualitative Analysis of Reservoir Pressure Capability

Operation experiences of free-piston driver indicate that an increased reservoir filling pressure can help to have a much quicker piston velocity with less acceleration time after the launch. Combination of faster piston speed and lighter piston can significantly reduce the requirement on compression tube length to reduce the facility construction cost and required space.

Qualitatively analysing, a reservoir having higher pressure capacity could help to ease the requirement of a longer compression tube and decrease the necessary piston mass. Furthermore, a shorter compression tube and lighter driver piston definitely decrease the overall facility cost.

As Equation 10 reflects, necessary piston mass has a converse-linear relationship with reservoir filling pressure, which in math guides that a higher reservoir filling pressure reduces the required piston mass with other parameters set.

8.7 Case Study 3 Conclusion

The trend lines all show a logarithmic growth characteristic;

Necessary piston mass increases as driver filling pressure increasing;

The average growth rate from 1~15 kPa is larger than that from 40~100 kPa;

For driver filling pressure lower than 10 kPa, the required piston mass would be always lower than 200 kg for a wide range of operation conditions;

A reservoir with higher capability is a one-off investment to ease the requirement of longer compression tube with relatively lighter piston when developing a certain flow condition.

The influence sensitivity of driver filling pressure is more intensive at lower numbers.

Chapter 9 Case Study 4 – A Study of Cost and Facility Scale

This chapter performs a rough study of the relationship between cost and facility scale of free-piston expansion tube. The data of this study was collected by looping the program presented in Chapter 5 . The data was sorted and demonstrated in the form of charts and tables within this chapter.

9.1 Condition

The set cost analysis condition is:

- Compression tube BORE range (mm): (330, 730)
- Ratio of Bore (Compression Tube over Shock Tube): 3
- Ratio of Length (Compression Tube over Shock Tube): 2
- Ratio of Length (Acceleration Tube over Shock Tube): 2. 8
- Ratio of Bore (Acceleration Tube over Shock Tube): 1

9.2 Result

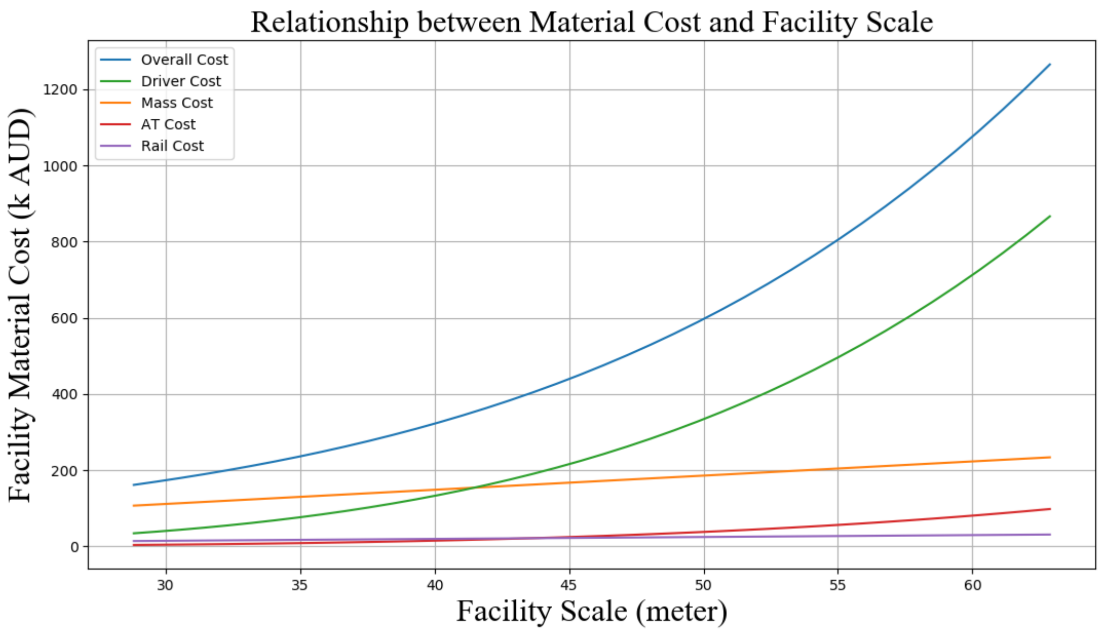


Figure 59. Relationship of Facility Cost to Scale

9.3 Discussion

Currently, we can have the information that material cost of driver dominates the overall facility material cost. If we consider processing cost into this model, the sensitivity of compression tube cost will be higher because driver requires much strict mechanical process standards.

The increase of facility shows an exponential trend. If we use MATLAB to further process the data of facility scale versus facility material cost, the results of facility cost versus scale are:

- f(x) = a*exp(b*x)
- Coefficients (with 95% confidence bounds):
- a = 29.75 (29.14, 30.35)
- b = 0.05981 (0.05945, 0.06018)
- Goodness of fit:
- SSE: 1005
- R-square: 0.9998
- Adjusted R-square: 0.9998
- RMSE: 5.142

The results of driver cost versus scale are:

- General model Exp 3:
- f(x) = a*exp(b*x)
- Coefficients (with 95% confidence bounds):
- a = 5.812 (5.054, 6.571)
- b = 0.08018 (0.07792, 0.08245)
- Goodness of fit:
- SSE: 1.01e+04
- R-square: 0.9957
- Adjusted R-square: 0.9956
- RMSE: 16.3

It can be known from the a-value, the driver cost gradually takes a larger proportion to the facility overall cost, which is from 17.3% to 21.65%. As for b-value. It shows that the overall facility cost increasing rate is lower than that of driver.

Please note that this cost is far away from the real construction cost because material processing and several facility components are not included:

- Safety Hardware (e.g. Fire-safety, High-pressure Gas Safety and Hazard Shelter etc…);
- Test Section;
- High-pressure Reservoir;
- Measurement Instrumentations (e.g. dynamical, optical and thermal etc…);
- Hydraulic System and Related Control;

- A lot of standardised mechanical parts (e.g. Flanges, Diaphragms, Bolts and Nuts etc…);
- Tailored parts (e.g. Nozzle, Buffer, Piston-launcher etc…);
- Computing Work Station;
- Gas storage;
- A lot of other costly things.

If we consider all the other components into the calculation, the sensitivity of compression tube cost might be influenced.

Chapter 10 Conclusion

This program (introduced in Chapter 5) is a very useful design tool, which would significantly assist the future X4 design team. This program has five modules which are:

- Dimension calculation;
- Tube wall thickness calculation;
- Necessary piston mass determination;
- Necessary inertial mass determination;
- Rough cost model.

By using the Program, two sets of X4 design with proposal scale of 40-meter and 60-meter were delivered and the results are summarised in Case Study 1 and Case Study 2. The cost of them are 323 thousand and 587 thousand respectively.

Besides implementing designing tasks, this Python based program was also used to complete a study of influence on permitted piston mass by varying single and dual operation condition variables.

Furthermore, a study of facility material cost versus facility scale was done by combining the core codes from 5 modules of the program, the results of which showed that the facility raw material cost had an exponential increasing trend as facility scale going up, The curve fitted mathematical model to explain this increase is Cost = a*exp(b*Scale) where a = 29.75 with range in (29.14, 30.35) and b = 0.05981 with range in (0.05945, 0.06018). The facility material cost study also indicated that the driver cost could gradually take a larger proportion to the facility overall cost, which is from 17.3% to 21.65%.

Chapter 11 Bibliography

The author would like to thank every researcher and scientist for sharing the profound discoveries.

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Chapter 12 Appendix

Part A

```python
global CT_Diameter
global CT_Length
global ST_Diameter
global ST_Length
global AT_Diameter
global AT_Length
global L_D_CT

from tkinter import *
import tkinter.messagebox as messagebox
class Dimension(Frame):
    def __init__(self,master = None):
        Frame.__init__(self,master)
        self.grid()
        self.inputCTandST()

    def inputCTandST(self):
        ##### Compression Tube Diameter (BORE)

        ##TEMP
        #self.calculateWTbutton = Button(self,text = 'Click to open a new window to calculate tube wall thckness.',command = CalWT.calculateWT).grid(row=0, column=4,padx=5,pady=5,sticky=NW)
        self.LabelCTD = Label(self,text = 'Please input Diameter of Compression Tube (mm):').grid(row=0,column=0,padx=5,pady=5,sticky=NW)#crate a notice to input CT
        self.inputCTD = Entry(self)#input CT Diameter
        self.inputCTD.grid(row=0,column=1,padx=5,pady=5,sticky=NW)

        ##### Compression Tube Length
        self.LabelCTL = Label(self,text = 'Please input Length of Compression Tube (mm):').grid(row=1,column=0,padx=5,pady=5,sticky=NW)#crate a notice to input CT L

        self.inputCTL = Entry(self)#input CT Length
        self.inputCTL.grid(row=1,column=1,padx=5,pady=5,sticky=NW)

        ##### Ratio to Determine Shock Tube Diameter
        self.LabelCT_ST_D = Label(self,text = 'Please Input Ratio of Diameter (Compression Tube/Shock Tube) Here:').grid(row=2,column=0,padx=5,pady=5,sticky=NW)
        #crate a notice to input CT_ST Diameter
        self.inputCT_ST_D = Entry(self)#input ratio CT_ST Diameter
        self.inputCT_ST_D.grid(row=2,column=1,padx=5,pady=5,sticky=NW)
        self.LabelCT_ST_D_hint = Label(self,text = '(Recommendation ratio: 3):').grid(row=2,column=2,padx=5,pady=5,sticky=NW)

        ##### Ratio to Determine Shock Tube Length
        self.LabelCT_ST_L = Label(self,text = 'Please Input Ratio of Length (Compression Tube/Shock Tube) Here:').grid(row=3,column=0,padx=5,pady=5,sticky=NW)
        #crate a notice to input ratio CT_ST Length
        self.inputCT_ST_L = Entry(self)#input ratio CT_ST Length
        self.inputCT_ST_L.grid(row=3,column=1,padx=5,pady=5,sticky=NW)
        self.LabelCT_ST_L_hint = Label(self,text = '(Recommendation ratio: 2):').grid(row=3,column=2,padx=5,pady=5,sticky=NW)

        #### Calculate the Dimension of Shock Tube
        self.calculateSTbutton = Button(self,text = 'Calculate the Dimension of Shock Tube',command = self.calculateST).grid(row=4,column=0,padx=5,pady=20,sticky=NW)

    def calculateST(self):
        global ST_Diameter
        global ST_Length
        CT_Diameter = float(self.inputCTD.get())
        CT_Length = float(self.inputCTL.get())
```

```

        ST_Diameter = float(self.inputCTD.get())/float(self.inputCT_ST_D.get())
        ST_Length = float(self.inputCTL.get())/float(self.inputCT_ST_L.get())

        #####
        self.LabelST_D = Label(self,text = 'The Calculated Shock Tube Diameter is (%s mm).'%ST_Diameter).grid(row=5,column=0,padx=5,pady=5,sticky=NW)
        #crate a notice to input ratio CT_ST Length

        #####
        self.LabelST_L = Label(self,text = 'The Calculated Shock Tube Length is (%s mm).'%ST_Length).grid(row=6,column=0,padx=5,pady=5,sticky=NW)
        #crate a notice to input ratio CT_ST Length

        #####
        self.LabelST_AT_D = Label(self,text = 'Please Input Ratio of Diameter (Acceleration Tube/Shcok Tube): ').grid(row=7,column=0,padx=5,pady=5,sticky=NW)
        #crate a notice to input ratio of ST_AT_D
        self.inputST_AT_D= Entry(self)#input ratio ST_AT_D
        self.inputST_AT_D.grid(row=7,column=1,padx=5,pady=5,sticky=NW)
        self.LabelST_AT_D_hint = Label(self,text = '(Recommendation ratio: 1 )').grid(row=7,column=2,padx=5,pady=5,sticky=NW)

        #####
        self.LabelST_AT_L = Label(self,text = 'Please Input Ratio of Length (Acceleration Tube/Shcok Tube)').grid(row=8,column=0,padx=5,pady=5,sticky=NW)
        #crate a notice to input ratio of ST_AT_L
        self.inputST_AT_L= Entry(self)#input ratio ST_AT_L
        self.inputST_AT_L.grid(row=8,column=1,padx=5,pady=5,sticky=NW)
        self.LabelST_AT_L_hint = Label(self,text = '(Recommendated range of ratio: [ 0.9 , 3.3 ] )').grid(row=8,column=2,padx=5,pady=5,sticky=NW)

        #### Calculate the Dimension of Acceleration Tube
        self.calculateSTbutton = Button(self,text = 'Calculate the Dimension of Acceleration Tube',command = self.calculateAT).grid(row=9,column=0,padx=5,pady=20,sticky=NW)

        return ST_Diameter, ST_Length

    def calculateAT(self):
        global ST_Diameter
        global ST_Length
        global AT_Diameter
        global AT_Length

        AT_Diameter = ST_Diameter * float(self.inputST_AT_D.get())
        AT_Length = ST_Length * float(self.inputST_AT_L.get())

        ##crate a notice to input ratio CT_ST Length
        self.LabelAT_D = Label(self,text = 'The Calculated Acceleration Tube Diameter is (%s mm).'%AT_Diameter).grid(row=10,column=0,padx=5,pady=5,sticky=NW)


        ##crate a notice to input ratio CT_ST Length
        self.LabelAT_L = Label(self,text = 'The Calculated Acceleration Tube Length is (%s mm).'%AT_Length).grid(row=11,column=0,padx=5,pady=5,sticky=NW)


        ## Demonstrate the results so far
        self.calculateSTbutton = Button(self,text = 'Demonstrate the Results so far',command = self.demonstration).grid(row=12,column=0,padx=5,pady=5,sticky=NW)

    def demonstration(self):
        global CT_Diameter
        global CT_Length
        global ST_Diameter
        global ST_Length
        global AT_Diameter
```

```
        global AT_Length
        global L_D_CT

        L_D_CT = round(float(self.inputCTL.get())/float(self.inputCTD.get()),3) #

        self.demoCT = Label(self,text = 'Compression Tube: Diameter (%s mm), Length (%s mm), Length/Diameter (%s).'%(self.inputCTD.get(),self.inputCTL.get(),L_D_CT)).grid(row=13,column=1,padx=5,pady=5,sticky=NW)
        self.demoST = Label(self,text = 'Shock Tube: Diameter (%s mm), Length (%s mm)'%(ST_Diameter,ST_Length)).grid(row=14,column=1,padx=5,pady=5,sticky=NW)
        self.demoAT = Label(self,text = 'Acceleration Tube: Diameter (%s mm), Length (%s mm)'%(AT_Diameter,AT_Length)).grid(row=15,column=1,padx=5,pady=5,sticky=NW)
        self.demoOverallLength = Label(self,text = 'The Total Length of your expansion tube is (%s mm)'%(float(self.inputCTL.get())+ST_Length+AT_Length)).grid(row=16,column=1,padx=5,pady=5,sticky=NW)
        #self.demoCT = Label(self,text = 'Length (%s mm).'%self.inputCTL.get()).grid(row=13,column=1,padx=0,pady=20,sticky=NW)
        #self.demoCTL = Label(self,text = 'The Calculated Acceleration Tube Length is (%s m).'%AT_Length).grid(row=11,column=0,padx=5,pady=5,sticky=NW)
        #self.LabelAT_D = Label(self,text = 'The Calculated Acceleration Tube Diameter is (%s mm).'%AT_Diameter).grid(row=10,column=0,padx=5,pady=5,sticky=NW)
        #self.LabelAT_L = Label(self,text = 'The Calculated Acceleration Tube Length is (%s m).'%AT_Length).grid(row=11,column=0,padx=5,pady=5,sticky=NW)
        #self.LabelAT_D = Label(self,text = 'The Calculated Acceleration Tube Diameter is (%s mm).'%AT_Diameter).grid(row=10,column=0,padx=5,pady=5,sticky=NW)
        #self.LabelAT_L = Label(self,text = 'The Calculated Acceleration Tube Length is (%s m).'%AT_Length).grid(row=11,column=0,padx=5,pady=5,sticky=NW)
        self.drawButton = Button(self,text = 'Click to open a new window to demonstrate a schematic drawing.',command = self.draw).grid(row=17,column=0,padx=5,pady=20,sticky=NW)
        self.calculateWTbutton = Button(self,text = 'Click to open a new window to calculate tube wall thckness.',command = self.GetStep2).grid(row=18,column=0,padx=5,pady=20,sticky=NW)

        IndexDimensionResult= open("IndexDimensionResult.txt","w")
        IndexDimensionResult.write("CT_Diameter = %s \nST_Diameter = %s \nAT_Diameter = %s \nCT_Length = %s \nST_Length= %s \nAT_Length = %s"%(self.inputCTD.get(), ST_Diameter, AT_Diameter, self.inputCTL.get(), ST_Length, AT_Length))
        IndexDimensionResult.close

        DimensionResult = open("DimensionResult.txt","w")
        DimensionResult.write("%s\n%s\n%s\n%s\n%s\n%s"%(self.inputCTD.get(), ST_Diameter, AT_Diameter, self.inputCTL.get(), ST_Length, AT_Length))
        DimensionResult.close

    def GetStep2(self):
        import Step2CalWT

    def draw(self):#This function is to demonstrate the overall dimension using a schematic
        CT_Diameter = float(self.inputCTD.get())
        CT_Length = float(self.inputCTL.get())

        DrawET = Toplevel(self)
        DrawET = Canvas(DrawET)
        DrawET.pack()
        DrawET.create_rectangle(10, 10, CT_Diameter, CT_Length)
        #messagebox.showinfo('Message','The Diameter of CT is set to %s m' %CT_Diameter)
        #messagebox.showinfo('Message','The Length of CT is set %s m' %CT_Length)

app1 = Dimension()
app1.master.title("Step 1 Tube Dimension - Free-Piston Driven Expansion Tube Calculator by Ye FU")#title
app1.mainloop()#End
```

Part B

```
from tkinter import *

from PIL import Image

f = open('DimensionResult.txt', 'r')
ETDimension = f.readlines()      #results from step 1
f.close()
    #DimensionResult Index:
    ##CT_Diameter float(ETDimension[0])
    ##ST_Diameter float(ETDimension[1])
    ##AT_Diameter float(ETDimension[2])
    ##CT_Length float(ETDimension[3])
    ##ST_Length float(ETDimension[4])
    ##AT_Length float(ETDimension[5])

CWT = Tk()
CWT.title("Step 2 Tube Wall Thickness Calculation - Free Piston Driven Expansion Tube Calculator by Ye FU")

global DesignPressure
global DesignTemp
global DesignStrength
global WeldJointFactor
global ClassDesignFactor
global CastingQualityFactor
global WeldJointStrengthReductionFactor

global CT_TF
global ST_TF
global AT_TF

global CT_TM
global ST_TM
global AT_TM

global G_CT
global G_ST
global G_AT

def CalWTinput():
  InformationClick = Label(CWT,text = 'Click the Button to Show Information from Australia Standards AS 4041-2006.R2016 (CopyRight: Standards Australia). ').grid(row=0,columnspan = 3,padx=5,pady=5,sticky=E+W)

  LabelDesignPressure = Button (CWT,text = 'Design Pressure:',command =OpenWTDesignPressure).grid(row=1,column=0,padx=5,pady=5,sticky=E+W)
  CWT.InputDesignPressure = Entry (CWT)
  CWT.InputDesignPressure.grid(row=1,column=1,padx=5,pady=5,sticky=NW)
  #InputDesignPressure.set('Entry') #set initial value of Entry

  LabelDesignTemp = Button (CWT,text = 'Design Temperature:',command = OpenWTDesignTemp).grid(row=2,column=0,padx=5,pady=5,sticky=E+W)
  CWT.InputDesignTemp = Entry(CWT)
  CWT.InputDesignTemp.grid(row=2,column=1,padx=5,pady=5,sticky=NW)


  LabelDesignStrength = Button (CWT,text = 'Design Strength:',command = OpenWTDesignStrength).grid(row=3,column=0,padx=5,pady=5,sticky=E+W)
  CWT.InputDesignStrength = Entry(CWT)
  CWT.InputDesignStrength.grid(row=3,column=1,padx=5,pady=5,sticky=NW)

```

```
    LabelWeldJointFactor = Button (CWT,text ='Weld Joint Factor:',command = OpenWTWeldJointFactor).grid(row=4,column=0,padx=5,pady=5,sticky=E+W)
    CWT.InputWeldJointFactor= Entry(CWT)
    CWT.InputWeldJointFactor.grid(row=4,column=1,padx=5,pady=5,sticky=NW)

    LabelClassDesignFactor = Button (CWT,text = 'Class Design Factor:',command = OpenWTClassDesignFactor).grid(row=5,column=0,padx=5,pady=5,sticky=E+W)
    CWT.InputClassDesignFactor= Entry(CWT)
    CWT.InputClassDesignFactor.grid(row=5,column=1,padx=5,pady=5,sticky=NW)

    LabelCastingQualityFactor = Button (CWT,text = 'Casting Quality Factor:',command = OpenWTCastingQualityFactor).grid(row=6,column=0,padx=5,pady=5,sticky=E+W)
    CWT.InputCastingQualityFactor= Entry(CWT)
    CWT.InputCastingQualityFactor.grid(row=6,column=1,padx=5,pady=5,sticky=NW)

    LabelWeldJointStrengthReductionFactor = Button (CWT,text = 'Weld Joint Strength Reduction Factor:',command = OpenWTWeldJointStrengthReductionFactor).grid(row=7,column=0,padx=5,pady=5,sticky=E+W)
    CWT.InputWeldJointStrengthReductionFactor= Entry(CWT)
    CWT.InputWeldJointStrengthReductionFactor.grid(row=7,column=1,padx=5,pady=5,sticky=NW)

    CalculateTFbutton = Button (CWT,text = 'Click to Calculate Ttube Pressure Design Wall Thckness (t_f) ',command = TFcalculateWT).grid(row=8,columnspan=3,padx=5,pady=5,sticky=NW)
    Label(CWT,text = '( Notice: Required Wall Thickness (t_m) = Pressure Design Wall Thickness (t_f) + Allowances (G) )').grid(row=9,columnspan=3,padx=5,pady=5,sticky=NW)

def TFcalculateWT():
    global CT_TF
    global ST_TF
    global AT_TF
    # let's get the inputted parameters
    DesignPressure = float(CWT.InputDesignPressure.get())
    DesignTemp =  float(CWT.InputDesignTemp.get())
    DesignStrength = float(CWT.InputDesignStrength.get())
    WeldJointFactor = float(CWT.InputWeldJointFactor.get())
    ClassDesignFactor = float(CWT.InputClassDesignFactor.get())
    CastingQualityFactor = float(CWT.InputCastingQualityFactor.get())
    WeldJointStrengthReductionFactor = float(CWT.InputWeldJointStrengthReductionFactor.get())

    #calculate
    CT_TF = round((DesignPressure*float(ETDimension[0]))/(2*DesignStrength*WeldJointFactor*ClassDesignFactor*WeldJointStrengthReductionFactor+DesignPressure),3)
    ST_TF = round((DesignPressure*float(ETDimension[1]))/(2*DesignStrength*WeldJointFactor*ClassDesignFactor*WeldJointStrengthReductionFactor+DesignPressure),3)
    AT_TF = ST_TF

    # to add some line margins in GUI
    Give_the_results_some_space_ok = Label(CWT,text = '').grid(row=10,column=0,padx=5,pady=5,sticky=NW)

    # demonstrate the calculation results of wall thickness for ct st and at
    Label(CWT,text = ' The Pressure Design Wall Thickness (t_f) for Compression Tube is: ( %s mm ).'%CT_TF).grid(row=13,column=0,columnspan=2,padx=5,pady=5,sticky=NW)
    Label(CWT,text = ' The Pressure Design Wall Thickness (t_f) for Shock Tube is: ( %s mm ).'%ST_TF).grid(row=14,column=0,columnspan=2,padx=0,pady=5,sticky=NW)
    Label(CWT,text = ' The Pressure Design Wall Thickness (t_f) for Acceleration Tube is: ( %s mm ).'%AT_TF).grid(row=15,column=0,columnspan=2,padx=5,pady=5,sticky=NW)

    # to add some line margins in GUI
    Give_the_results_some_space_ok = Label(CWT,text = '').grid(row=17,column=0,padx=5,pady=5,sticky=NW)

    LabelAllowancesCT = Label(CWT,text = 'Allowances for Compression Tube (G_CT):').grid(row=19,column=0,padx=5,pady=5,sticky=E+W)
```

```
    CWT.InputAllowancesCT= Entry(CWT)
    CWT.InputAllowancesCT.grid(row=19,column=1,padx=5,pady=5,sticky=NW)

    LabelAllowancesST = Label(CWT,text = 'Allowances for Shock Tube (G_ST):').grid(row=20,column=0,padx=5,pady=5,sticky=E+W)
    CWT.InputAllowancesST = Entry(CWT)
    CWT.InputAllowancesST.grid(row=20,column=1,padx=5,pady=5,sticky=NW)

    LabelAllowancesAT = Label(CWT,text = 'Allowances for Acceleration  Tube (G_AT):').grid(row=21,column=0,padx=5,pady=5,sticky=E+W)
    CWT.InputAllowancesAT = Entry(CWT)
    CWT.InputAllowancesAT.grid(row=21,column=1,padx=5,pady=5,sticky=NW)

    CalTMbutton = Button (CWT,text = 'Click to Calculate Ttube Required Wall Thckness (t_m) ', command = TMcalculateWT).grid(row=22,column=0,padx=5,pady=5,sticky=NW)

    return CT_TF, ST_TF, AT_TF

def TMcalculateWT():
    global CT_TF
    global ST_TF
    global AT_TF
    global CT_TM
    global ST_TM
    global AT_TM
    G_CT = float(CWT.InputAllowancesCT.get())
    G_ST = float(CWT.InputAllowancesST.get())
    G_AT = float(CWT.InputAllowancesAT.get())
    CT_TM = G_CT+CT_TF
    ST_TM = G_ST+ST_TF
    AT_TM = G_AT+AT_TF

    Label(CWT,text = 'The Required Wall Thickness (t_m) for Compression Tube is: ( %s mm ).'%CT_TM).grid(row=19,column=3,padx=5,pady=5,sticky=NW)
    Label(CWT,text = 'The Required Wall Thickness (t_m) for Shock Tube is: ( %s mm ).'%ST_TM).grid(row=20,column=3,padx=5,pady=5,sticky=NW)
    Label(CWT,text = 'The Required Wall Thickness (t_m) for Acceleration Tube is: ( %s mm ).'%AT_TM).grid(row=21,column=3,padx=5,pady=5,sticky=NW)

    Button (CWT, text = 'Click to Demonstrate the Dimension (Outside Diameter)  ',command = ODResult ).grid(row=22,column=3,padx=5,pady=5,sticky=NW)

def ODResult():
    global CT_TM
    global ST_TM
    global AT_TM

    global CT_OD
    global ST_OD ## OD ---- outside diameter
    global AT_OD
#calculate the Outside diameters
    CT_OD = float(ETDimension[0])+2*CT_TM
    ST_OD = float(ETDimension[1])+2*ST_TM
    AT_OD = float(ETDimension[2])+2*AT_TM

    Label(CWT,text = 'The Outside Diameter of Compression Tube is: ( %s mm ).'%(float(ETDimension[0])+2*CT_TM)).grid(row=19,column=4,padx=5,pady=5,sticky=NW)
    Label(CWT,text = 'The Outside Diameter of Shock Tube is: ( %s mm ).'%(float(ETDimension[1])+2*ST_TM)).grid(row=20,column=4,padx=5,pady=5,sticky=NW)
    Label(CWT,text = 'The Outside Diameter of Acceleration Tube is: ( %s mm ).'%(float(ETDimension[2])+2*AT_TM)).grid(row=21,column=4,padx=5,pady=5,sticky=NW)

    #output bore results to txt for data transfer
    IndexODResult= open("IndexODResult.txt","w")
    IndexODResult.write("CT_OD = %s \nST_OD = %s \nAT_OD = %s \nCT_Length = %s \nST_Length= %s \nAT_Length = %s"%(CT_OD,ST_OD , AT_OD, float(ETDimension[3]), float(ETDimension[4]), float(ETDimension[5])))
    IndexODResult.close
```

```

  ODResult = open("ODResult.txt","w")
  ODResult.write("%s\n%s\n%s\n%s\n%s\n%s"%(CT_OD,ST_OD,AT_OD, float(ETDimension[3]), float(ETDimension[4]), float(ETDimension[5])))
  ODResult.close

  Button (CWT, text = 'Click to Implement the Analysis to Determine the Necessary Driver Pison Mass',command = directtostep3 ).grid(row=23, column=0,columnspan = 3, padx=5,pady=5,sticky=NW)

def directtostep3():
  import Step3StalkerAnalysis

# functions to add more parameter meanings when clicking the button, a image clarifying the meaning of inputted parameter will be shown
def OpenWTDesignPressure():
  Image.open('WTDesignPressure.png').show()

def OpenWTDesignTemp():
  Image.open('WTDesignPressure.png').show()

def OpenWTDesignStrength():
  Image.open('WTDesignStrength.png').show()

def OpenWTWeldJointFactor():
  Image.open('WTWeldJointFactor.png').show()
def OpenWTClassDesignFactor():
  Image.open('WTClassDesignFactor.png').show()

def OpenWTCastingQualityFactor():
  Image.open('WTCastingQualityFactor.png').show()

def OpenWTWeldJointStrengthReductionFactor():
  Image.open('WTWeldJointStrengthReductionFactor.png').show()

CalWTinput() #first run function to start this part
CWT.mainloop()#end
```

Part C

```python
from tkinter import *

import matplotlib.pyplot as plt
import numpy
import math

#### Ideal gases and lossless processes are assumed

f = open('DimensionResult.txt', 'r')
ETDimension = f.readlines()     # line by line
f.close()

#DimensionResult Index:
    ##CT_Diameter float(ETDimension[0])
    ##ST_Diameter float(ETDimension[1])
    ##AT_Diameter float(ETDimension[2])
    ##CT_Length float(ETDimension[3])
    ##ST_Length float(ETDimension[4])
    ##AT_Length float(ETDimension[5])

#f = open('ODResult.txt', 'r')
#ETubeOD = f.readlines()     # line by line
#f.close()

##bore result index
##CT_OD float(ETubeOD[0])
##ST_OD
##AT_OD
##CT_Length
##ST_Length
##AT_Length


global k ##satefy sactor for satalker analysis
## Den - non-dimensional driver demsity
## z - non-dimensional time  #peak driver pressure occurs at z = 0 ## diaphragm rupture must occur for z <= 0

StalkerAnalysis = Tk()
StalkerAnalysis.title("Step 3 Determine the Necessary Piston Mass - Free-Piston Driven Expansion Tube Calculator by Ye FU")

def Input():
    Information = Label(StalkerAnalysis,text = 'Stalker Analysis (Reference: R. J. Stalker, A study of the free-piston shock tunnel. AIAA Journal, 1967. 5(12): p. 2160-2165). ').grid(row=0,columnspan = 5,padx=5,pady=5,sticky=E+W)
    Label(StalkerAnalysis,text = 'Please input the Stalker k parameter which is suggested to be 1: ').grid(row=3,column= 0,padx=5,pady=5,sticky=E+W)
    StalkerAnalysis.input = Entry(StalkerAnalysis)
    StalkerAnalysis.input.grid(row=3,column= 1,padx=5,pady=5,sticky=E+W)

    Button (StalkerAnalysis, text= 'Click to demonstrate the non-dimensionalised relationship between driver density (D) and time (z) of Stalker Analysis with your inputted k. ', command= plot).grid(row=3, column= 2,columnspan = 5,padx=5,pady=5,sticky=E+W)
    Button (StalkerAnalysis, text= ' Solve z values for a ±10% driver pressure variation', command= solvez).grid(row=7, column= 0,padx=5,pady=5,sticky=E+W)

def plot():
    global k
    global D
```

```
    k = float(StalkerAnalysis.input.get())

    if k==1:
        z = numpy.arange(-1,1,0.01)
        qwe = numpy.arctan((k*z - 1)/((2*k-1)**(-1/2)))
        rty = numpy.arctan(-1/ (2*k-1)**(-1/2))
        uio = numpy.exp(-2 / (2*k-1)**(-1/2) * (qwe - rty))
        D = (1/(1 - z + ((z**2)* k/2))) * uio

        indicator1 = plt.axhline(0.9*max(D), color = 'r',linestyle ='--')
        indicator2 = plt.axhline(0.8*max(D), color = 'r', label ='±10% driver pressure variation indication line',linestyle ='--')
        indicator3 = plt.axhline(max(D), color = 'r', linestyle ='--')

    else:
        if k == 0.5:
            z = numpy.arange(-3,1.9,0.01)
            D = (1/(1 - z + ((z**2)* k/2)))
        else:
            z = numpy.arange(-3,1.9,0.01)
            qwe = numpy.arctan((k*z - 1)/((2*k-1)**(-1/2)))
            rty = numpy.arctan(-1/ (2*k-1)**(-1/2))
            uio = numpy.exp(-2 / (2*k-1)**(-1/2) * (qwe - rty))
            D = (1/(1 - z + ((z**2)* k/2))) * uio    #D = (1/(1 - z + ((z**2)* k/2))) * math.exp(-2 / ((2*k-1)**(-1/2)) * (numpy.arctan((k*z - 1)/((2*k-1)**(-1/2))) - numpy.arctan(-1/ ((2*k-1)**(-1/2)))))

    plt.title(' Non-dimensionalised relationship between driver density (D) and time (z) of Stalker Analysis when k = %s. '%k)
    plt.xlabel('z\nz = U_r * t / x_r', fontsize = 16)
    plt.ylabel('ρ_D / ρ_D,r', fontsize = 16)
    plt.plot(z, D)

    plt.grid(ON)
    plt.legend()
    plt.show()
    return D

def solvez():

    global D
    global k

    Label(StalkerAnalysis,text = 'The ±10 %% driver pressure variation result when k=%s is: \nSelected rupture point = (%s, %s); \nVariation point (-10 %%) = (%s, %s );\nVariation point (+10 %%) = (%s, %s) '%(k, 0.4054,0.9*max(D),0.4465,0.8*max(D),1.0,max(D))).grid(row=9, column= 0,columnspan=5,padx=5,pady=5,sticky=E+W)
    Button (StalkerAnalysis, text= ' Click to begin further Stalker Analysis for your design', command= pistonmass1).grid(row=13, column= 0,padx=5,pady=5,sticky=E+W)
    #z = U_r* t * x_r
    #u/U_r = 1 - k*z

def pistonmass1():

    global CompressionRatio
    global RupturePressure
    global RatioSpecificHeatDriver
    global RatioSpecificHeatReservoir
    global ReservoirFillPressure
    global Length

    ##compression ratio
    Label (StalkerAnalysis, text= ' 1. Please input a proposal compression ratio (λ): ').grid(row=15, column= 0,padx=5,pady=5,sticky=NW)
    StalkerAnalysis.CompressionRatio = Entry (StalkerAnalysis)
```

```
    StalkerAnalysis.CompressionRatio.grid(row=15, column= 1,padx=5,pady=5,sticky=E+W)

    ## Stalker Analysis L - Length between piston front surface and the primary diaphragm
    Label (StalkerAnalysis, text= ' 2. Please input the Length (L) (unit: mm) :').grid(row=17, column= 0,padx=5,pady=5,sticky=NW)
    StalkerAnalysis.Length = Entry (StalkerAnalysis)
    StalkerAnalysis.Length.insert(END,'%s mm'%float(ETDimension[3]))
    StalkerAnalysis.Length.grid(row=17, column= 1,padx=5,pady=5,sticky=NW)
    Label (StalkerAnalysis, text= 'The length between the piston front surface and the primary diaphragm; Hint: your length in Step 1 of CT is (%s mm ).'%float(ETDimension[3])).grid(row=17, column= 2,padx=5,pady=5,sticky=NW)

    ##compression tube area
    ## Primary Diaphragm Rupture Pressure
    Label (StalkerAnalysis, text= '3. Please input a Primary Diaphragm Rupture Pressure (MPa):').grid(row=21, column= 0, padx=5,pady=5,sticky=NW)
    StalkerAnalysis.RupturePressure = Entry (StalkerAnalysis)
    StalkerAnalysis.RupturePressure.grid(row=21, column= 1, padx=5,pady=5,sticky=E+W)

    ### gas compositions
    # gas compositions driver gas_ratio of  specific heats
    Label (StalkerAnalysis, text= '4. Please input your Ratio of Specific Heats of Driver Gas (γ_D):').grid(row=23, column= 0, padx=5,pady=5,sticky=NW)
    StalkerAnalysis.RatioSpecificHeatDriver = Entry (StalkerAnalysis)
    StalkerAnalysis.RatioSpecificHeatDriver.grid(row=23, column= 1, padx=5,pady=5,sticky=E+W)
    Label (StalkerAnalysis, text= '100% Helium: 1.667; 100% Argon: 1.667; 100% Air = 1.4; Gas temperature is assumed to 23 deg.C').grid(row=23, column= 2,padx=5,pady=5,sticky=NW)

    #gas compositions RatioSpecificHeatReservoir gas_ratio of  specific heats
    Label (StalkerAnalysis, text= '5. Please input your Ratio of Specific Heats of Reservoir Gas (γ_A):').grid(row=25, column= 0, padx=5,pady=5,sticky=NW)
    StalkerAnalysis.RatioSpecificHeatReservoir = Entry (StalkerAnalysis)
    StalkerAnalysis.RatioSpecificHeatReservoir.grid(row=25, column= 1, padx=5,pady=5,sticky=E+W)

    ##    initial reservoir fill pressure   ## use this part is Reservoir filling pressure is desired to be repeated
    ##    Label (StalkerAnalysis, text= '6. Please input your Reservoir Fill Pressure (p_A_0, MPa):').grid(row=27, column= 0, padx=5,pady=5,sticky=NW)
    ##    StalkerAnalysis.ReservoirFillPressure = Entry (StalkerAnalysis)
    ##    StalkerAnalysis.ReservoirFillPressure.grid(row=27, column= 1, padx=5,pady=5,sticky=E+W)

    ##    initial driver fill pressure
    Label (StalkerAnalysis, text= '6. Please input your Driver Fill Pressure (p_D_0, MPa):').grid(row=29, column= 0, padx=5,pady=5,sticky=NW)
    StalkerAnalysis.DriverFillPressure = Entry (StalkerAnalysis)
    StalkerAnalysis.DriverFillPressure.grid(row=29, column= 1, padx=5,pady=5,sticky=E+W)

    ##    gas constant
    Label (StalkerAnalysis, text= '7. Please input your Driver gas constant (R_D, J/(kg*K):').grid(row=31, column= 0, padx=5,pady=5,sticky=NW)
    StalkerAnalysis.DriverGasConstant = Entry (StalkerAnalysis)
    StalkerAnalysis.DriverGasConstant.grid(row=31, column= 1, padx=5,pady=5,sticky=E+W)
    Label (StalkerAnalysis, text= '100% Helium: R = 2077.1; 100% Argon: R = 208.13. Driver gas temperature is assumed to 23 deg.C').grid(row=31, column= 2,padx=5,pady=5,sticky=NW)

    ## speed of sound
    Label (StalkerAnalysis, text= '8. Please input reservoir gas Speed of Sound (m/s)').grid(row=32, column= 0, padx=5,pady=5,sticky=NW)
```

```
    StalkerAnalysis.SpeedofSound = Entry (StalkerAnalysis)
    StalkerAnalysis.SpeedofSound.grid(row=32, column= 1, padx=5,pady=5,sticky=E+W)
    Label (StalkerAnalysis, text= ' Helium: a = 972 m/s; Argon: a = 307.85 m/s; Air 20 deg.C: a = 343 m/s. Gas temperature is assumed to 23 deg.C').grid(row=32, column= 2,padx=5,pady=5,sticky=NW)

    ##choose a Reservoir Filling Pressure
    Label (StalkerAnalysis, text= '9. Please try a Reservoir Filling Pressure in MPa ').grid(row=33, column= 0, padx=5,pady=5,sticky=NW)
    StalkerAnalysis.ReservoirFillPressure = Entry (StalkerAnalysis)
    StalkerAnalysis.ReservoirFillPressure.grid(row=33, column= 1, padx=5,pady=5,sticky=E+W)
    Label (StalkerAnalysis, text= ' Chosse a Reservoir Filling Pressure and then calculate piston response u_rupture at x_r; Iterate through until poston mass until u_r = 1.4054 U_r').grid(row=33, column= 2,padx=5,pady=5,sticky=NW)


    Label (StalkerAnalysis, text= '10. The Compression Tube bore of your design was (%s mm). Thus, the CT area A is approximate (%s m^2).'%(round(float(ETDimension[0]),4),round(float(ETDimension[0])*float(ETDimension[0])*numpy.pi/1e6,3))).grid(row=35, column= 0, columnspan=3,padx=5,pady=5,sticky=NW)
    Button (StalkerAnalysis, text= ' Click to meet the calculated piston mass of this run for your design', command= pistonmass2).grid(row=37, column= 0,padx=5,pady=5,sticky=E+W)

def pistonmass2():
    global Length
    Length_m = float(StalkerAnalysis.Length.get())/1000
    global CompressionRatio # λ
    CompressionRatio = float(StalkerAnalysis.CompressionRatio.get())
    global RuptureCompressionRatio # λ_r

    global RupturePressure # p_D_r
    RupturePressure = float(StalkerAnalysis.RupturePressure.get())

    global RatioSpecificHeatDriver # γ_D
    RatioSpecificHeatDriver = float(StalkerAnalysis.RatioSpecificHeatDriver.get())

    global RatioSpecificHeatReservoir # γ_A
    RatioSpecificHeatReservoir = float(StalkerAnalysis.RatioSpecificHeatReservoir.get())

    global PistonMass #PistonMass =  float(StalkerAnalysis.PistonMass.get())

    global ReservoirFillPressure # p_A_0
    ReservoirFillPressure = float(StalkerAnalysis.ReservoirFillPressure.get())

    global DriverFillPressure
    DriverFillPressure = float(StalkerAnalysis.DriverFillPressure.get())

    global x_r # the piston position, distance between piston front face and primary diaghragm \done
    global u_rupture # the velocity of piston when rupturing \done
    global U_r # the velocity of postion when rupturing without ±10 %% driver pressure variation \done

    global R_D #driver gas constant J/(kg*K) \done
    R_D = float(StalkerAnalysis.DriverGasConstant.get())

    global T_D_0 # driver gas temperature\done
    global SpeedofSound # reservior gas SoS
    SpeedofSound = float(StalkerAnalysis.SpeedofSound.get())

    T_D_0 = 23 + 273.15 #driver gas temperature
    CTArea_m= (float(ETDimension[0])*float(ETDimension[0])*2*numpy.pi)/(1e+6)
    #calculation λ_rupture
```

```
    RuptureCompressionRatio = CompressionRatio / 0.9**(1/RatioSpecificHeatDriver) ## calculate rupture compression ratio, 0.9 is determined by the ±10 %% driver pressure variation
    ##calculation x_r
    x_r = Length_m / RuptureCompressionRatio
    ##calculation U_r and u_rupture
    U_r =round((((2/(RatioSpecificHeatDriver+1))**((RatioSpecificHeatDriver+1)/(2*(RatioSpecificHeatDriver-1))))* 9 * ((RatioSpecificHeatDriver*R_D*T_D_0*(RupturePressure/DriverFillPressure)**((RatioSpecificHeatDriver-1)/RatioSpecificHeatDriver))**(0.5)))**(0.5),3)
    u_rupture = (1 - 1*(-0.4054))*U_r
    PistonMass = (RupturePressure - ReservoirFillPressure* (1- (0.5*RatioSpecificHeatReservoir-1)*(1.4*U_r/SpeedofSound))**(2*RatioSpecificHeatReservoir/(RatioSpecificHeatReservoir-1))) * (Length_m*float(ETDimension[0])*float(ETDimension[0])*numpy.pi/RuptureCompressionRatio/U_r/U_r)

    ## calculation ReservoirFillPressure
    #ReservoirFillPressure =  round((RupturePressure - (PistonMass*U_r**U_r*RuptureCompressionRatio)/(Length_m*CTArea_m))*(1-((RatioSpecificHeatReservoir-1)/2)*(u_rupture/SpeedofSound))**(-2*RatioSpecificHeatReservoir/(RatioSpecificHeatReservoir-1)),2)

    Label (StalkerAnalysis, text= 'The input Compresstion Ratio λ = (%s) and Rupture Compression Ratio (λ_r) = %s' %(CompressionRatio,round(RuptureCompressionRatio,3))).grid(row=41, column= 0, padx=5,pady=5,sticky=NW)
    Label (StalkerAnalysis, text= 'The piston distance to primary diaphragm is %s m' %round(x_r,3)).grid(row=42, column= 0, padx=5,pady=5,sticky=NW)
    Label (StalkerAnalysis, text= 'The piston velocity (u) when rupturing is u_rupture = %s m/s with U_r = %s m/s' %(round(u_rupture,3), U_r)).grid(row=43, column= 0, padx=5,pady=5,sticky=NW)
    Label (StalkerAnalysis, text= 'The input Compresstion Ratio λ = (%s) and Rupture Compression Ratio (λ_r) = %s' %(CompressionRatio,round(RuptureCompressionRatio,3))).grid(row=44, column= 0, padx=5,pady=5,sticky=NW)
    Label (StalkerAnalysis, text= 'The calculated piston mass for this try is = %s kg' %round(PistonMass,2)).grid(row=45, column= 0, padx=5,pady=5,sticky=NW)

Input()

StalkerAnalysis.mainloop()#
```

Part D

```python
from tkinter import *

import numpy
import math


#### Ideal gases and lossless processes are assumed

f = open('DimensionResult.txt', 'r')

ETDimension = f.readlines()     # line by line

f.close()

#DimensionResult Index:
    ##CT_Diameter float(ETDimension[0])
    ##ST_Diameter float(ETDimension[1])
    ##AT_Diameter float(ETDimension[2])
    ##CT_Length float(ETDimension[3])
    ##ST_Length float(ETDimension[4])
    ##AT_Length float(ETDimension[5])

##f = open('BoreResult.txt', 'r')
##
##ETBore = f.readlines()     # line by line
##
##f.close()


##bore result index
##CT_Bore  float(ETBore[0])
##ST_Diameter
##AT_Diameter
##CT_Length
##ST_Length
##AT_Length


InertialMass = Tk()
InertialMass.title("Step 4 Calculation of Necessary Inertial Mass - Free-Piston Driven Expansion Tube Calculator by Ye FU")

def okk():

    Label(InertialMass,text = 'Please input the Piston Mass m_piston in kg ').grid(row=0,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.pistonmass = Entry(InertialMass)
    InertialMass.pistonmass.grid(row=0,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = 'Your calculated m_piston in Step 3 is (181.61 kg) ').grid(row=0,column= 2,padx=5,pady=5,sticky=NW)

    Label(InertialMass,text = 'Please input the piston impact velocity v_impact in m/s').grid(row=5,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.Vimpact = Entry(InertialMass)
    InertialMass.Vimpact.grid(row=5,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = 'Your calculated piston velocity at rupture moment in Step 3 is (236  m/s) ').grid(row=5,column= 2,padx=5,pady=5,sticky=NW)

    Label(InertialMass,text = 'Please input the tube strength in MPa ').grid(row=7,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.TubeStrength = Entry(InertialMass)
    InertialMass.TubeStrength.grid(row=7,column= 1,padx=5,pady=5,sticky=NW)
```

```python

    Label(InertialMass,text = "Please input the tube material Young's modulus in GPa ").grid(row=8,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.YoungM = Entry(InertialMass)
    InertialMass.YoungM.grid(row=8,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = '(Normally 210 GPa for steel) ').grid(row=8,column= 2,padx=5,pady=5,sticky=NW)

    Label(InertialMass,text = "Please input the tube material density in kg/m^3 ").grid(row=9,column= 0,padx=5,pady=5,sticky=NW)
    InertialMass.Density = Entry(InertialMass)
    InertialMass.Density.grid(row=9,column= 1,padx=5,pady=5,sticky=NW)
    Label(InertialMass,text = '(Normally 8000 kg/m^3 for steel) ').grid(row=9,column = 2,padx=5,pady=5,sticky=NW)

    Button (InertialMass, text= 'Click to calculate the  inertial mass ', command= inertialmass).grid(row=10, column= 0,columnspan = 1,padx=5,pady=20,sticky=E+W)


def inertialmass():

    global pistonmass
    global Vimpact
    global TubeStrength
    global YoungM
    global Voverall
    global TES ##tensile elastic stress unit  MPa/(m/s)
    global Density
    global inertialM

    pistonmass = float(InertialMass.pistonmass.get())
    Vimpact = float(InertialMass.Vimpact.get())
    TubeStrength = float(InertialMass.TubeStrength.get())
    YoungM = float(InertialMass.YoungM.get())
    Density = float(InertialMass.Density.get())

    TES = round(numpy.sqrt(Density * YoungM * 1000000000)/1000000,4)

    Voverall = round(TubeStrength/TES,3)

    inertialM = round((pistonmass * Vimpact)/Voverall,1)

    Label(InertialMass,text = ' The calculated tensile elastic stress caused by impact is (%s MPa/(m/s)) '%TES).grid(row=14,column= 0,columnspan = 3, padx=5,pady=5,sticky=W)
    Label(InertialMass,text = ' The calculated maximum allowable V_overall (departure velocity of piston and tube) by impact is (%s m/s) '%Voverall).grid(row=16,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(InertialMass,text = ' The calculated minimum ratio of m_inertial / m_piston is %s '%round((Vimpact/Voverall),3)).grid(row=17,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(InertialMass,text = ' The calculated minimum inertial mass is (%s kg) '%inertialM).grid(row=18,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)



okk()

InertialMass.mainloop()#
```

Part E

```
from tkinter import *

import numpy
import math


#### Ideal gases and lossless processes are assumed

f = open('DimensionResult.txt', 'r')

ETDimension = f.readlines()      # line by line

f.close()

#DimensionResult Index:
    ##CT_Diameter float(ETDimension[0])
    ##ST_Diameter float(ETDimension[1])
    ##AT_Diameter float(ETDimension[2])
    ##CT_Length float(ETDimension[3])
    ##ST_Length float(ETDimension[4])
    ##AT_Length float(ETDimension[5])

f = open('ODResult.txt', 'r')

ETOD = f.readlines()      # line by line

f.close()


##bore result index
##CT_OD  float(ETOD[0])
##ST_Diameter
##AT_Diameter
##CT_Length
##ST_Length
##AT_Length


CostModel = Tk()
CostModel.title("Step 5 Rough Cost Model - Free-
Piston Driven Expansion Tube Calculator by Ye FU")

def okk():

    Label(CostModel,text = 'Please input the Compression Tube BORE and OD in meter '
).grid(row=0,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.CTBore = Entry(CostModel)
    CostModel.CTBore.grid(row=0,column= 1,padx=5,pady=5,sticky=NW)
    CostModel.CTOD = Entry(CostModel)
    CostModel.CTOD.grid(row=0,column= 2,padx=5,pady=5,sticky=NW)
    Label(CostModel,text = 'Your Compression Tube Bore in Step 1 is (%s mm) and OD i
n Step 2 is (%s mm)'%(float(ETDimension[0]),float(ETOD[0]))).grid(row=0,column= 3,pa
dx=5,pady=5,sticky=NW)

    Label(CostModel,text = 'Please input tthe Compression Tube Length in meter').gri
d(row=1,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.CTL = Entry(CostModel)
    CostModel.CTL.grid(row=1,column= 1,padx=5,pady=5,sticky=NW)
    Label(CostModel,text = 'Your Compression Tube Length Step 1 is (%s mm) '%(float(
ETDimension[3]))).grid(row=1,column= 3,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = 'Please input the Shock Tube Bore and OD in m ').grid(row
=2,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.STBore = Entry(CostModel)
    CostModel.STBore.grid(row=2,column= 1,padx=5,pady=5,sticky=NW)
```

```
    CostModel.STOD = Entry(CostModel)
    CostModel.STOD.grid(row=2,column= 2,padx=5,pady=5,sticky=NW)
    Label(CostModel,text = 'Your Shock Tube Bore in Step 1 is (%s mm) and OD in Step 2 is (%s mm)'%(float(ETDimension[1]),float(ETOD[1]))).grid(row=2,column= 3,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = 'Please input tthe Shock Tube Length in meter').grid(row=3,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.STL = Entry(CostModel)
    CostModel.STL.grid(row=3,column= 1,padx=5,pady=5,sticky=NW)
    Label(CostModel,text = 'Your Compression Tube Length Step 1 is (%s mm) '%(float(ETDimension[4]))).grid(row=3,column= 3,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = 'Please input the Acceleration Tube Bore and OD in m ').grid(row=4,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.ATBore = Entry(CostModel)
    CostModel.ATBore.grid(row=4,column= 1,padx=5,pady=5,sticky=NW)
    CostModel.ATOD = Entry(CostModel)
    CostModel.ATOD.grid(row=4,column= 2,padx=5,pady=5,sticky=NW)
    Label(CostModel,text = 'Your Shock Tube Bore in Step 1 is (%s mm) and OD in Step 2 is (%s mm)'%(float(ETDimension[2]),float(ETOD[2]))).grid(row=4,column= 3,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = 'Please input tthe Acceleration Tube Length in meter').grid(row=5,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.ATL = Entry(CostModel)
    CostModel.ATL.grid(row=5,column= 1,padx=5,pady=5,sticky=NW)
    Label(CostModel,text = 'Your Acceleration Tube Length Step 1 is (%s mm) '%(float(ETDimension[5]))).grid(row=5,column= 3,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = "Please input the inertial mass in tonne").grid(row=6,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.InertialMass = Entry(CostModel)
    CostModel.InertialMass.grid(row=6,column= 1,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = "Please input a piston mass in kg").grid(row=7,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.PistonMass = Entry(CostModel)
    CostModel.PistonMass.grid(row=7,column= 1,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = "Please input a rough tube material price in AUD/tonne").grid(row=8,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.TubePrice = Entry(CostModel)
    CostModel.TubePrice.grid(row=8,column= 1,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = "Please input a rough inertial mass material price in AUD/tonne").grid(row=9,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.MassPrice = Entry(CostModel)
    CostModel.MassPrice.grid(row=9,column= 1,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = "Please input a rail dimension Length x Width x Height in meter").grid(row=10,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.RailLength = Entry(CostModel)
    CostModel.RailLength.grid(row=10,column= 1,padx=5,pady=5,sticky=NW)
    CostModel.RailWidth = Entry(CostModel)
    CostModel.RailWidth.grid(row=11,column= 1,padx=5,pady=5,sticky=NW)
    CostModel.RailHeight = Entry(CostModel)
    CostModel.RailHeight.grid(row=12,column= 1,padx=5,pady=5,sticky=NW)

    Label(CostModel,text = '').grid(row=13,column= 0,padx=5,pady=5,sticky=NW) ##space

    Label(CostModel,text = "Please input a rough steel section bar (for rail) material price in AUD/tonne").grid(row=14,column= 0,padx=5,pady=5,sticky=NW)
    CostModel.RailPrice = Entry(CostModel)
    CostModel.RailPrice.grid(row=14,column= 1,padx=5,pady=5,sticky=NW)

```

```
    Button (CostModel, text= 'Click to calculate the cost ', command= okCost).grid(row=15, column= 0,columnspan = 1,padx=5,pady=20,sticky=E+W)


def okCost():

    global CTBore #input m
    global CTOD #input m
    global CTL #input m
    global STBore #input m
    global STOD #input m
    global STL #input m
    global ATBore #input m
    global ATOD #input m
    global ATL #input m
    global InertialMass #inpout tonne
    global PistonMass #inpout kg
    global TubePrice # AUD/tonne
    global MassPrice # AUD/tonne
    global RailLength
    global RailWidth
    global RailHeight
    global RailPrice

    SteelDensity = 8 #tonne/m^3

    CTBore = float(CostModel.CTBore.get())
    CTOD = float(CostModel.CTOD.get())
    CTL = float(CostModel.CTL.get())


    STBore = float(CostModel.STBore.get())
    STOD = float(CostModel.STOD.get())
    STL = float(CostModel.STL.get())

    ATBore = float(CostModel.ATBore.get())
    ATOD = float(CostModel.ATOD.get())
    ATL = float(CostModel.ATL.get())

    InertialMass = float(CostModel.InertialMass.get())
    PistonMass_tonne = float(CostModel.PistonMass.get())/1000

    TubePrice = float(CostModel.TubePrice.get())
    MassPrice = float(CostModel.MassPrice.get())

    RailLength = float(CostModel.RailLength.get())
    RailWidth = float(CostModel.RailWidth.get())
    RailHeight = float(CostModel.RailHeight.get())

    RailPrice = float(CostModel.RailPrice.get())


    CTCost = round(numpy.pi* (CTOD*CTOD - CTBore*CTBore) *CTL* SteelDensity * TubePrice,4)
    STCost = round(numpy.pi*(STOD*STOD - STBore*STBore)*STL* SteelDensity * TubePrice,4)
    ATCost = round(numpy.pi*(ATOD*ATOD - ATBore*ATBore)*ATL* SteelDensity * TubePrice,4)

    TubeCost =round(CTCost+ATCost+STCost,2)
    MassCost = round((InertialMass + PistonMass_tonne)* MassPrice,2)
    RailCost = round(RailLength*RailWidth*RailHeight*RailPrice*SteelDensity,2)

    OverallCost = round(TubeCost + MassCost+RailCost,2)

    Label(CostModel,text = ' The calculated Compression Tube cost is (%s AUD) '%CTCost).grid(row=19,column= 0,columnspan = 3, padx=5,pady=5,sticky=W)
```

```
    Label(CostModel,text = ' The calculated Shock Tube cost is (%s AUD) '%STCost).grid(row=20,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(CostModel,text = ' The calculated Acceleration Tube cost is (%s AUD) '%ATCost).grid(row=21,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(CostModel,text = ' The calculated mass material cost is (%s AUD) '%MassCost).grid(row=22,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(CostModel,text = ' The calculated rail material cost is (%s AUD) '%RailCost).grid(row=23,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)
    Label(CostModel,text = ' The calculated overall facility material cost is (%s AUD), which is (%s thousand AUD) '%(OverallCost, round((OverallCost/1000)+1,2))).grid(row=24,column= 0,columnspan = 3,padx=5,pady=5,sticky=W)



okk()

CostModel.mainloop()#End
```