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2025 Engine Catalog

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

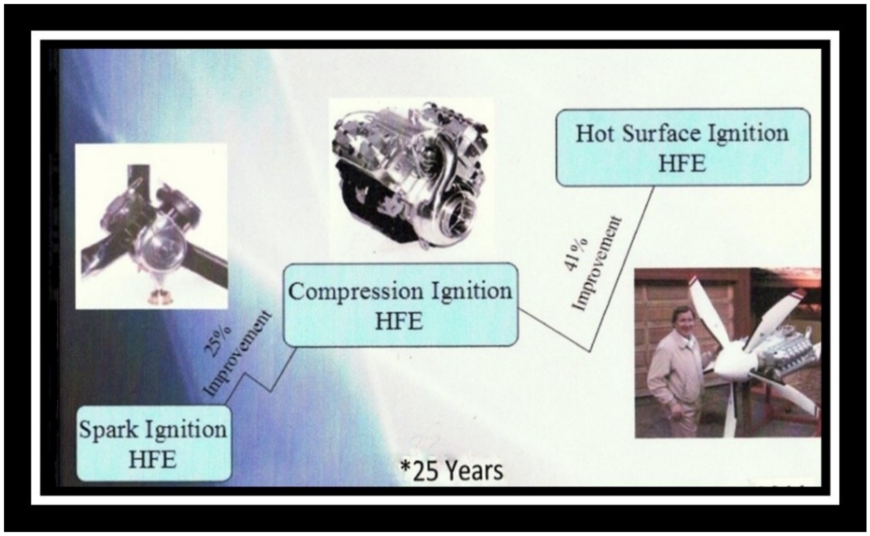
Acronym / Word	Definitions
“G“	Gravity
ALE	Air Launched Effects
ARL	Army Research Laboratory
ATP	Acceptance Test Procedure
AXI	Axial Engine Class
BMEP	Brake Mean Effective Pressure
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
C 58 Rockwell	Hardness indicator
C.G.	Center of Gravity
CAD/CAM	Computer Aided Design and Computer Aided Manufacturing
CEO	Company Executive Officer
CHSI™	Catalytic Hot Surface Igniter™
CI	Compression Ignition
CLT	Common Launch Tube
CM	Configuration Management
CNC	Computer Numerical Control
COTS	Commercial off the shelf
CPM	Critical Path Method
CR	Compression Ratio
DEP	Distributed Electric Propulsion
DF-2	Diesel Fuel #2
DFI	Direct Fuel Injection
DI	Direct Injection
DRE	Direct Replacement Engine
DSE	Dynamic Systems Engineering
EAA	Experimental Aircraft Association
EFI	Electronic Fuel Injection
EPA	Environmental Protection Agency
ERC	Engine Run Cut

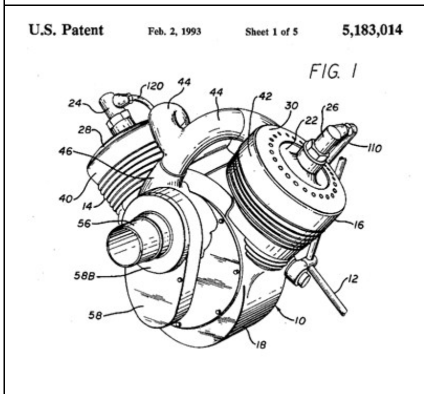
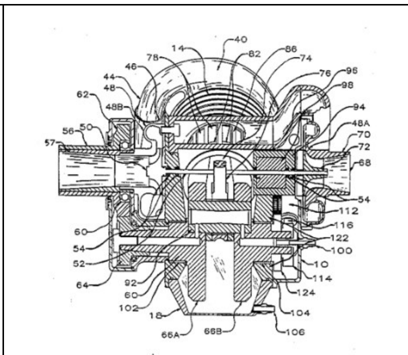
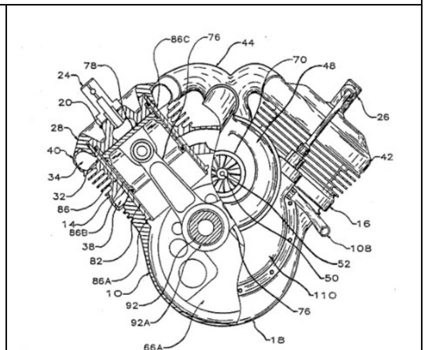
Acronym / Word	Definitions
ESSP	Efficient Small-Scale Propulsion
ETC	Estimate to Completion
F-1	Formula-1 Racing
FCA	Functional Configuration Audit
FCD	Functional Configuration Documentation
FDR	Final Design Review
FPT	Free-Piston
FRACAS	Failure Report and Corrective Action System
g/kw-hr	Grams per Kilowatt Hour
GFE	Government Furnished Equipment
GHG	Greenhouse Gases
GSE	G.S. Engineering
GSIO	Geared Supercharger Injected Opposed
HECM™	Hyper Expansion Crank Mechanism™
HFE	Heavy Fuel Engine
hp	Horsepower
Hrs	Hours
IAS	Indicated Air Speed
IC	Intermittent Ignition
IDR	Initial Design Review
IL	Inline Engine Class
INA	INA Bearing Manufacturer
IO	Injected Opposed Engine Class
IPT	International Project Team
ISO	International Standards Organization
JAR 22	Joint Airworthiness Requirements Section 22
JP-5 / JP-8 / F-24	Various Kerosene based Jet Fuels
Kw	Kilowatt
lbs	Pounds
lbs/bhp	Pounds per Brake Horsepower
lbs/hp/hr	Pounds per Horsepower per Hour

Acronym / Word	Definitions
LCAAT	Low Cost Attritable Aircraft Technology
LiPo	Lithium polymer battery
M.S.	Master of Science
MCOTS	Modified Commercial off the shelf
MFI	Mechanical Fuel Injection
MTBF	Mean Time Between Failure
MTBO	Mean Time Between Overhaul
NASA	National Space and Science Administration
NLT	Not Later Than
OMC	Outboard Marine Corporation
OPV	Optionally Piloted Vehicle
PA	Project Authorizations
PCA	Product Configuration Audit
PCD	Product Configuration Documentation
PMP	Project Management Plan
PSI	Pounds per Square Inch
RON	Rated Octane Number
Rpm	Revolutions per minute
RTD	Resistance Temperature Device
SHP	Shaft Horsepower
SI	Standard Ignition
SICPS	Standard Integrated Command Post System
SIO	Supercharged Injected Opposed Engine Class
SIV	Supercharged Injected “V” Engine Class
SOW	Statement of Work
SPE™	Split Personality Engine™
STP	Standard Temperature and Pressure
TBO	Time Between Overhauls
TCIO	Turbo-Compound Injected Opposed Engine Class
TIO	Turbocharged Injected Opposed Engine Class
TIV	Turbocharged Injected V Engine Class

Acronym / Word	Definitions
TPE	Turbine Powered Engine
TSFC	Thrust Specific Fuel Consumption
UAV	Unmanned Arial Vehicle
VAMPS™	Vortex Ancillary Modular Propulsion System
VCRV™	Variable Compression Ratio Valve™
VPA™	Variable Position Atomizer™
WBS	Work Breakdown Structure
Wh/kg	Watt Hours per Kilogram

1. GSE ENGINE CATALOG



Original micro turbo-compound engine patent for UAV propulsion 1987.		
		

1.1. Group I Engine Catalog (1~15hp)

IL-58 / 2-Cycle / 3.2 shp

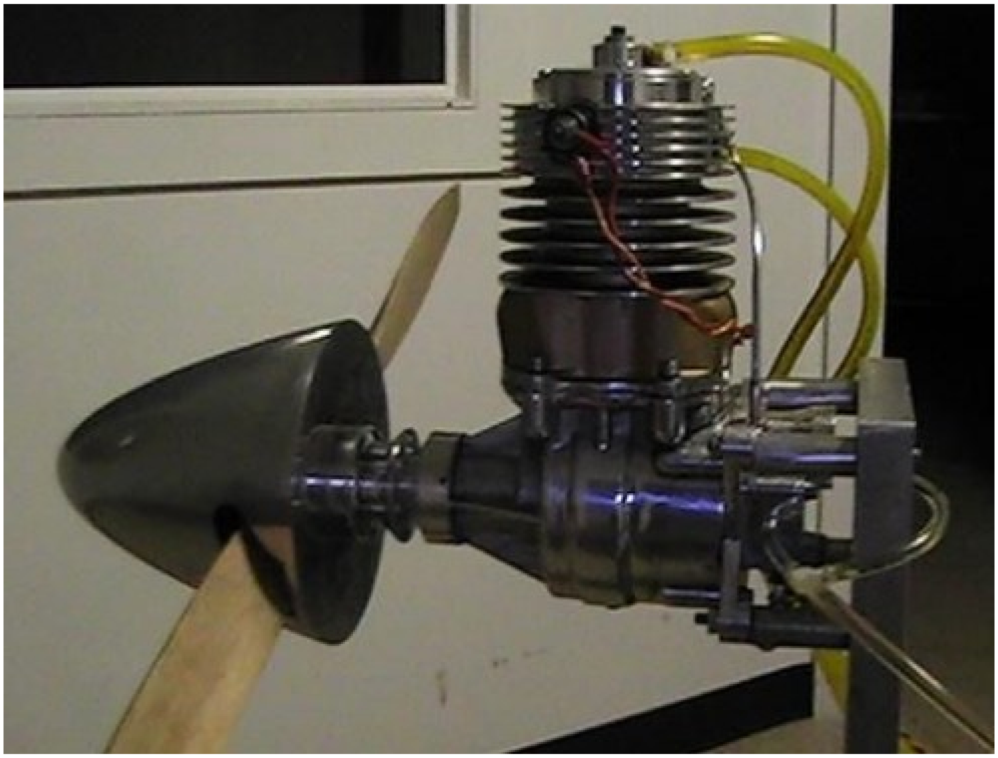

- Great Horned Owl

Engine Type / Configuration	Air Cooled / Single Cylinder
Bore x Stroke = Displacement	42mm x 42mm = 58.16cc (3.55 in^3)
Induction / Supercharge	Naturally Aspirated
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	3.2 hp @ 5500 RPM / BMEP = 56 psi
Surface / Volume Ratio	2.15 in^2 / 3.55 in^3 = 0.61:1
Fuel Consumption / Cruise	0.56 lbs/hp-hr @ 5500 RPM
Specific Power	3.2 hp / 3.55 in^3 = 0.90 hp / in^3
Specific Weight	3.2 hp / 4.5 lbs = 0.71 hp / lb
Specific Volume	6.3L x 4.5W x 8.5H = 22.95 hp / ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The IL-58 is a modern high speed liquid cooled loop scavenge 2-cycle engine of maximum volumetric efficiency and power output from five inlet transfer and two exhaust ports. The integral liquid cooled head is fitted with a horizontally prone igniter and cylindrical combustion chamber to keep the profile of the engine as low as possible. Best performing Group I single cylinder with high specific output (1.43 hp/in^3), weight (1.12 hp/lb), volume (68 hp/ft^3).

ZDZ-80 / 2-Cycle / 4.2 shp



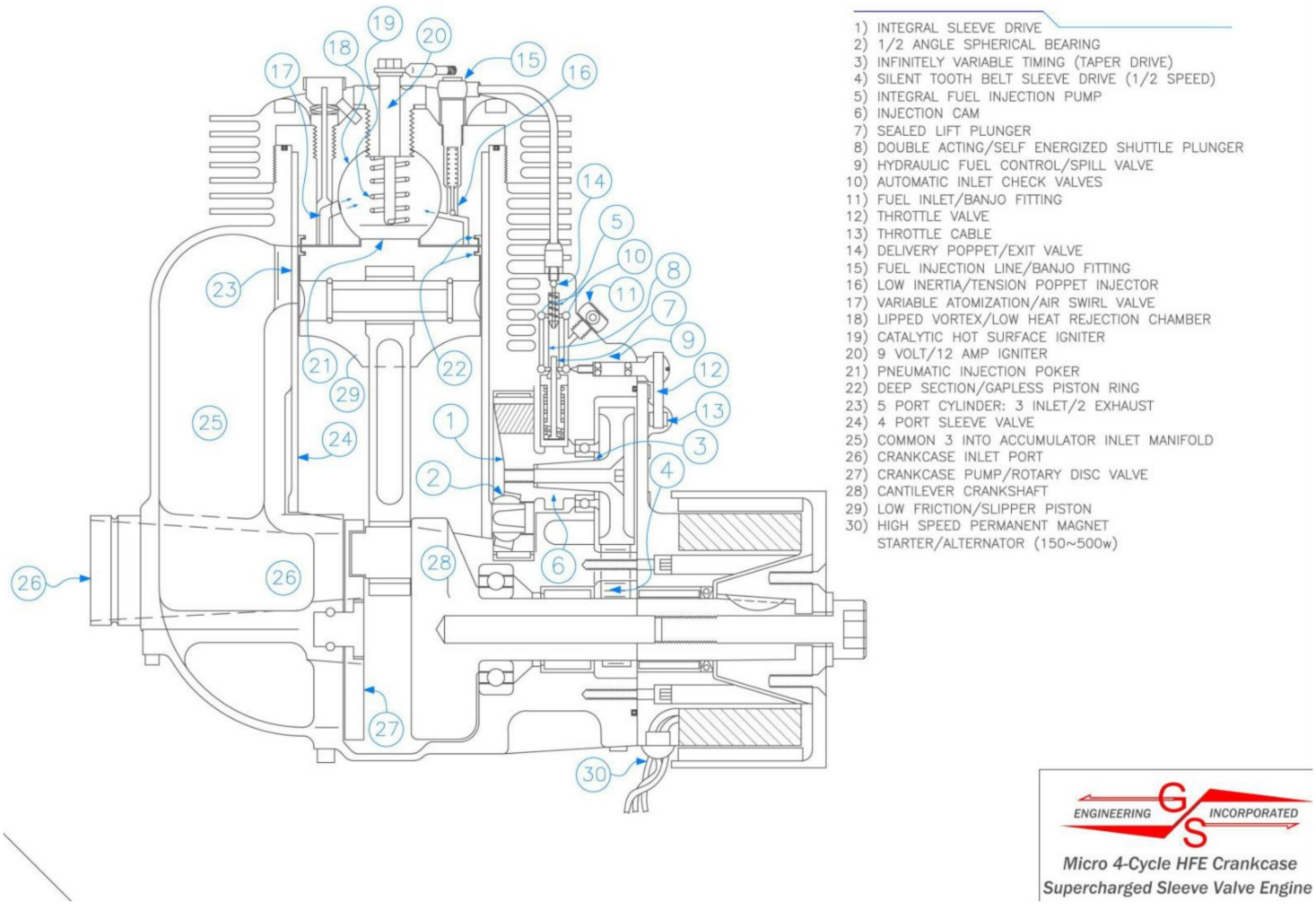
- Test Environment Engine

Engine Type / Configuration	Air Cooled / Single Cylinder
Bore x Stroke = Displacement	46.5mm x 46.5mm = 79cc (4.74in^3)
Induction / Supercharge	Naturally Aspirated
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	4.2 hp @ 5500 RPM / BMEP = 64 psi
Surface / Volume Ratio	2.63 in^2 / 4.74 in^3 = 0.55:1
Fuel Consumption / Cruise	0.56 lbs/hp-hr @ 5500 RPM
Specific Power	4.2 hp / 4.74 in^3 = 0.886 hp / in^3
Specific Weight	4.2 hp / 4.5 lbs = 0.93 hp / lb
Specific Volume	6.3L x 4.5W x 8.5H = 30hp / ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The ZDZ-80 is a materials test rig engine for the purpose of developing multi-fuel combustion system strategies. It has a modest port timing and square bore stroke ratio while the rotary disc inlet valve enables good breathing for high-speed operation. The engine is naturally aspirated and fitted with a high silicon (17%) billet aluminum piston. The fuel is metered by an integral rotary plunger pump design as illustrated above. The liquid cooled cylinder head eliminates localized hot spots between the injector tip and the combustion chamber which is critical for turbine jet fuel operation.

SV-24 / 4-Cycle / 1.85 shp



SV-24 / 4-Cycle / 1.85 shp (Continued)

- **Army PUMA**

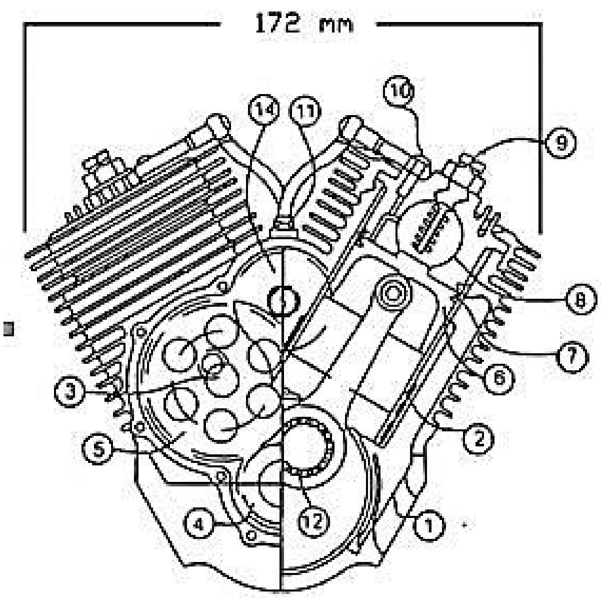
Engine Type / Configuration	Air Cooled / 4-Cycle Single Cylinder
Bore x Stroke = Displacement	32mm x 30mm = 24cc (1.44 in^3)
Induction / Supercharge	Crankcase Supercharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	1.85 hp @ 7,800 RPM / BMEP = 130 psi
Surface / Volume Ratio	1.246 in^2 / 1.44 in^3 = 0.86:1
Fuel Consumption / Cruise	0.78 lbs / hp-hr @ 75% Load
Specific Power	1.85 hp / 1.44 in^3 = 1.28 hp / in^3
Specific Weight	1.85 hp / 2.25 lbs = 0.82 hp / lb
Specific Volume	3.6L x 2.9W x 3.9H = 112 hp / ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

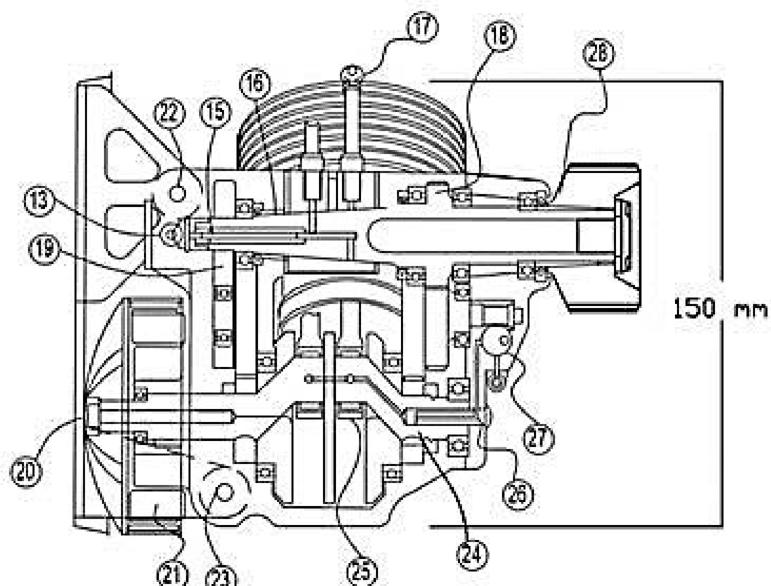
Premise:

The purpose-built sleeve valve (SV-24) engine is crankcase supercharged and represents a direct heavy fuel replacement to the popular 3W-24cc engine. It has 3 inlets and 2 exhaust ports controlled by the common sleeve valve resulting in maximum trapping efficiency and low thermal losses for high fuel efficiency. The compactness and lightweight construction make it an ideal candidate for either Group I hand launch UAS and/or portable power generation of 350~500 watts.

SIV-250 / 4-Cycle / 5.8 shp





SIV-250 / 4-Cycle / 5.8 shp (Continued)

Table 1 - SIV-250 Parts Labels

ITEM	Parameter	ITEM	Parameter
1	Crankcase Reed Inlet Valves	15	Common Rotary Plunger
2	Reciprocating Sleeve Valves	16	Conical Rotary Valve
3	Sleeve Drive Mechanism	17	Injector Port
4	Crankshaft Drive	18	Output Drive Gear
5	Sleeve Spur Gear	19	Fuel Pump
6	Heavy Duty Piston	20	Crank Retainer
7	High Duty Piston Rings	21	Out-Runner Motor/Generator
8	Multi-Fuel Combustion Chamber	22	Upper Motor Mount
9	Heavy Fuel Igniter	23	Lower Motor Mount
10	Fuel Injector	24	Lightweight Crankshaft
11	Fuel Pump Delivery Valve	25	Connecting Rods
12	Roller Bearing Crankshaft	26	Common Oil Port
13	Injection Pump Cam Follower	27	Lubrication Pump
14	Common Injection Pump	28	Output Flange

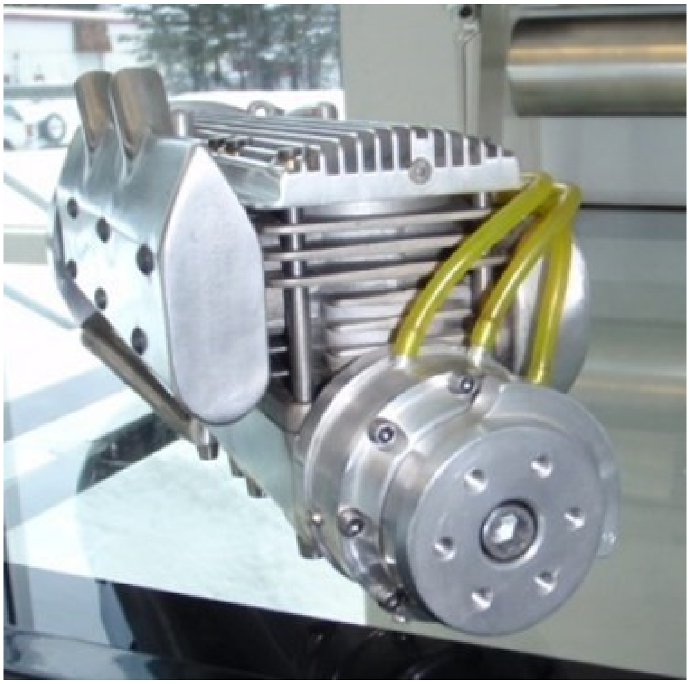
- ScanEagle II

Engine Type / Configuration	Air Cooled / 4-Cycle V-Twin (60 Degree) Sleeve Valve
Bore x Stroke = Displacement	(42mm x 36mm) x 2 = 100 cc (6 in^3)
Induction / Supercharge	Crankcase Supercharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	5.8 hp @ 7,500 RPM / BMEP = 204 psi
Surface / Volume Ratio	2.147 in^2 / 6 in^3 = 0.36:1
Fuel Consumption / Cruise	0.52 lbs / hp-hr @ 65% Load
Specific Power	5.8 hp / 6 in^3 = 0.96 hp / in^3
Specific Weight	5.8 hp / 6.25 lbs = 0.928 hp/lb
Specific Volume	7.4L x 6.8W x 7.5H = 26.5 hp / ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

Premise:

The SIV-250 is a 60-degree V-twin crankcase supercharged 4-cycle sleeve engine representing the top group I performance in terms of high altitude and low specific fuel consumption. The even fire crankpin geometry has the advantage of maximum volumetric and piston phasing relative to the wide-open port time area afforded by the alternative V-twin 4-cycle valve timing. The engine applications are intended for both fix wing (Scan Eagle) or rotary wing (Flexrotor) Group I UAS.

SIL-330 / 2-Cycle / 6.4 shp



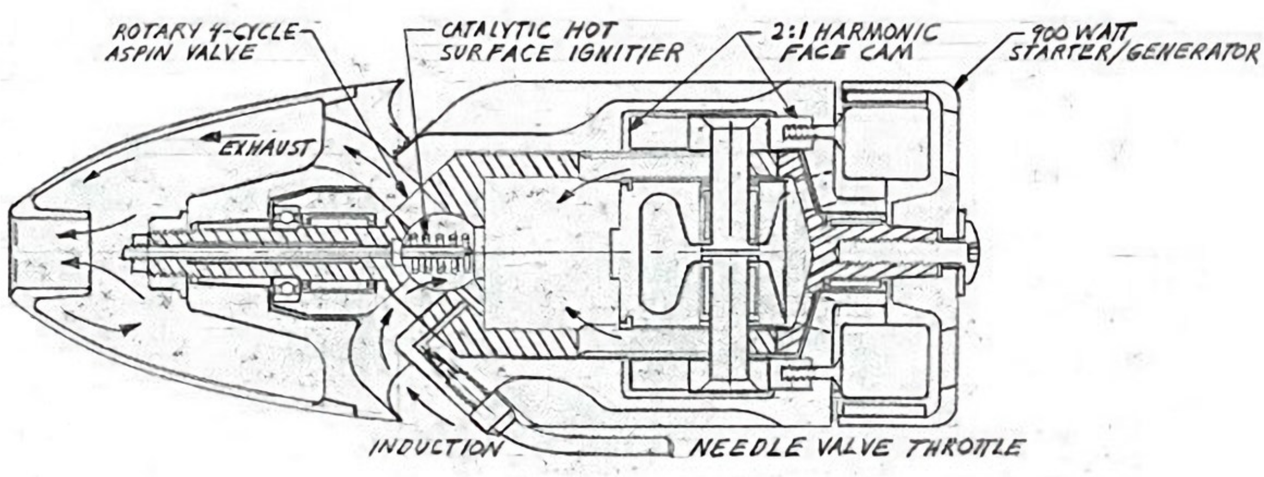
- Army Quicklook

Engine Type / Configuration	In-Line 3-Cylinder / 2-Cycle
Bore x Stroke = Displacement	(36mm x 30mm) x 3 = 91.5 cc (5.47 in^3)
Induction / Supercharge	Centrifugal Supercharge
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	6.4 hp @ 7,500 RPM / BMEP = 62psi
Surface / Volume Ratio	1.578 in^2 / 1.83 in^3 = 0.86:1
Fuel Consumption / Cruise	0.78 lbs/hp-hr @ 70% Load
Specific Power	6.4 hp / 5.49in^3 = 1.165 hp / in^3
Specific Weight	6.4 hp / 9.25 lbs = 0.69 hp / lb
Specific Volume	11.2L x 2.7W x 4.85H = 75 hp / ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

Premise:

The in-line 330 (IL-330) is a centrifugal supercharged in-line 91cc triple cylinder HFE of exceptionally compact frontal area intended for the original Army Quicklook tube launch program from a 155mm (6.1 in.) Howitzer barrel. The height of the engine was kept to a minimum by introducing a double segmented connecting rod geometry, much like the Napier Nomad. This enabled a suitable connecting rod ratio (1.6:1) while reducing frontal height by approximately 20%. The common air-cooled cylinder head with additional fin area and thickness providing stiffness to the engine.

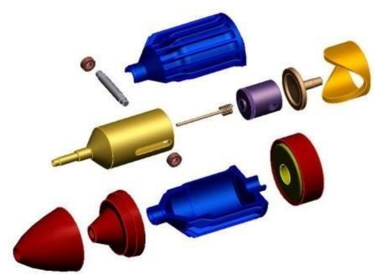
AXI-36 / 4-Cycle / Supercharged / 2.1 shp



COMMON LAUNCH TUBE: AXIAL SUPERCHARGED INJECTED-36cc (CLT: ASI-36/HFE)

Conceptual View

Sectional View



Exploded View

- Army Quicklook

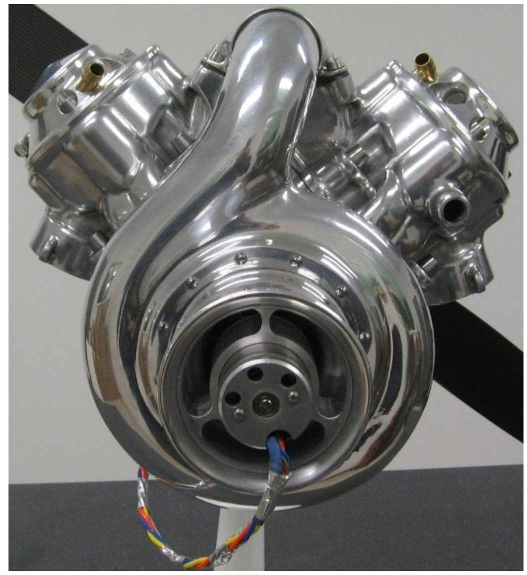
Engine Type / Configuration	Axial Single Cylinder / 4-Cycle / Supercharged
Bore x Stroke = Displacement	38mm x 32mm = 36cc (2.16in^3)
Induction / Supercharge	
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	2.1 hp @ 4,800 RPM / BMEP = 76 psi
Surface / Volume Ratio	1.577in2 / 5.456in^3 = 0.45:1
Fuel Consumption / Cruise	0.65 lbs/hp-hr @ 70% Load
Specific Power	2.1 hp / 3.46in^3 = 0.607 hp/in^3
Specific Weight	2.1 hp / 3.5 lbs = 0.6 hp / lb
Specific Volume	2.75" Diameter x 6.1"L = 98hp / ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 4

Premise:

The axial injected 36 cc (AXI-36) engine is intended for the high-altitude Common Launch Tube (CLT) propulsion requirement as solicited by the Army under SBIR topic A20-112. The innovative compact 4-cycle engine is comprised of a symmetrical lobe dual face cam roller bearing crank assembly that delivers the 2:1 output while providing the conical valve timing in the cylinder head. The sealing of which is proportionate to the cylinder pressure while the combined rotary piston motion optimizes uniform heat transfer and dry sump lubrication independent of orientation Supercharging is by means of 1.6:1 crankcase delivery ratio. The CHSI™ igniter is pre-heated prior to launch, while the modified SIETEC fuel injection is both self-aspirating and governing. (i.e., Needle valve fuel control during suction stroke vs. operating speed).

1.2. Group II Engine Catalog (15~60hp)

SIV-90 / 2-Cycle / Supercharged / 16 shp



- DARPA ANCILLARY

Engine Type / Configuration	V-Twin (90 Degrees)/Supercharged 2-cycle
Bore x Stroke = Displacement	(44.5mm x 41.6mm) x 2 = 130cc (7.92 in^3)
Induction / Supercharge	Crankcase / Centrifugal Supercharge
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	16 hp @ 7,800 RPM / BMEP = 102 psi
Surface / Volume Ratio	4.8 in^2/7.92in^3 = 0.606:1
Fuel Consumption / Cruise	0.52 lbs/hp-hr @ 70% cruise
Specific Power	16hp/7.92 in^3 = 2.02 hp/in^3
Specific Weight	16hp/12.85lbs = 1.24 hp/lb
Specific Volume	10.3L x 9.8W x 9.8H = 0.57ft^3 / 16/0.57 = 28hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The original injected 90-degree V-twin (IV-90) was GSE's proposed solution for the original NAVAIR Ultra Endurance Heavy Fuel Engine (UE-HFE) program intended to power the emerging STUAS Boeing/Blackjack (RQ-21) UAS. Increased payload and GTOW lead to the introduction of the centrifugal supercharger (SIV-90) as illustrated here. The result is excess scavenge air delivery for maximum power output at high speeds (7,800 RPM) and altitude flat rating to (18,000 ft). Currently under several DARPA ANCILLARY VTOL platform bids.

SIV-300 / 2-Cycle / Supercharged / 24 shp

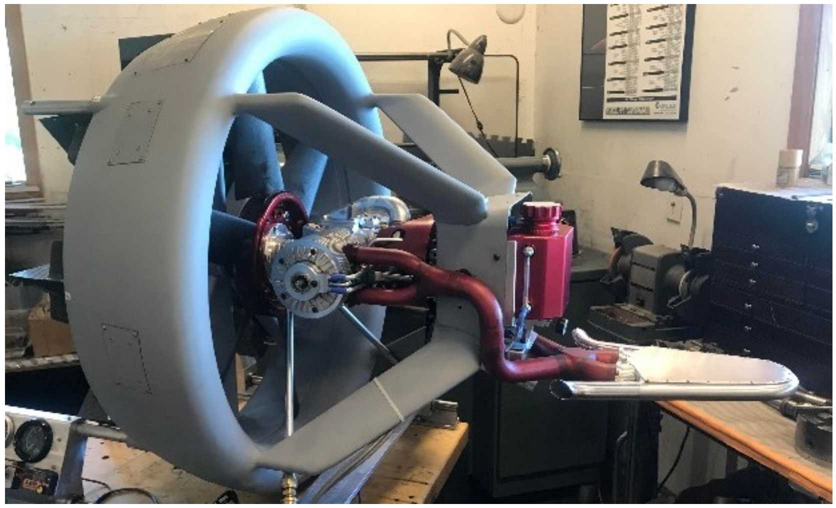
- FTUAS
- Shield AI
- AeroVironment Jump 20

Engine Type / Configuration	V-Twin (80 degrees)/Supercharged 2-cycle
Bore x Stroke = Displacement	(60mm x 54mm) x 2 = 294 cc (18.63 in^3)
Induction / Supercharge	Crankcase / Centrifugal Supercharge
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	24 hp @ 6,800 RPM / BMEP = 95 psi
Surface / Volume Ratio	8.76 in^2/ 18.63 in^3 = 0.47:1
Fuel Consumption / Cruise	0.48 lbs/hp-hr
Specific Power	24 hp/18.63 in^3 = 1.29 hp/in^3
Specific Weight	24 hp/21 lbs = 1.14 hp/lb
Specific Volume	9.8L x 10.4W x 10.7H = 0.63 ft^3 / 24/0.63 = 38 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The Supercharged Injected 80-degree V-twin SIV-300 was in response to numerous Army FT-UAS and Navy STUAS/DARPA ANCILLARY propulsion needs in the large Group II category. The baseline engine leverages the experience gained from the smaller SIV-90 development. The major design changes have been the incorporation of the 2:1 belt reduction drive along with the crank driven outrunner starter/motor generator. The fuel injection pumps driven on the backside of the half speed reduction drive housing in close proximity to the fuel injector mounted in the head. The design approach aimed at lower production cost from the incorporation of MCOTS components.

SIO-260F / 4-Cycle / Supercharged / 21 shp



- Northrup Grumman – V-Bat

Engine Type / Configuration	Flat Twin (180 degree) 4-cycle supercharged forward facing exhaust
Bore x Stroke = Displacement	(60mm x 46mm) x 2 = 260 cc (15.6 in^3)
Induction / Supercharge	Crankcase / 2:1 / Centrifugal Supercharge
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	21 hp @ 7500 RPM / BMEP = 142 psi
Surface / Volume Ratio	8.76 in^2/15.6 in^3 = 0.56:1
Fuel Consumption / Cruise	0.45 lbs/hp-hr
Specific Power	21hp/15.6 in^3 =1.34 hp/in^3
Specific Weight	21hp/17.6 lbs = 1.19 hp/lb
Specific Volume	10.7L x 15.2W x 6.7H = 0.63 ft^3 / 21/0.63 = 33 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The Supercharged Injected Opposed (SIO-260F) is a compact, lightweight flat opposed aircraft engine currently being developed for the Northrop V-BAT FT-UAS candidate. The frontal area being kept to the absolute minimum so as not to impede air flow through the ducted fan arrangement. The tuned exhaust is facing forward and collects into the muffler discharging reward. This 4-cycle sleeve valve has both external supercharge from the gear driven centrifugal blower as well as the internal 2:1 crankcase delivery ratio to the cylinders. Weight is kept to a minimum by the billet CNC mono-block cylinders and heads. The thin wall sleeve valves have required special tooling to achieve round cylinder bores.

SIV-540 / 4-Cycle / Supercharged / 25 shp

- DARPA ANCILLARY

Engine Type / Configuration	V-Twin (60 degree) 4-cycle Supercharged
Bore x Stroke = Displacement	(60mm x 48mm) x 2 = 540cc (16.2 in^3)
Induction / Supercharge	Crankcase / 2:1 / Centrifugal Supercharge
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	25 hp @ 7800 RPM / BMEP = 153 psi
Surface / Volume Ratio	8.76in2/16.2 in^3 = 0.54:1
Fuel Consumption / Cruise	0.48 lbs/hp-hr
Specific Power	25 hp/16.2 in^3 = 1.54 hp/in^3
Specific Weight	25 hp/21.8 lbs = 1.15 hp/lb
Specific Volume	9.3L x 8.2W x 9.1H = 0.396 / 25hp/0.396 = 63hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

Similar in operation to the flat opposed SIO-260F, the even fire 60-degree Turbocharged Injected Vee (TIV-540) is a more compact variation. The primary balance weights are built into the single piece billet crankshaft, while the sleeve valves are phased 180 degrees apart and share the same overlapping crankcase volume. This engine was built for the Boeing RQ-21 Blackjack Navy STUAS aircraft but has been relegated to a low priority now that the DARPA ANCILLARY program has redefined the larger VTOL aircraft.

SIV-600 / 4-Cycle / Supercharged / 50 shp / Liquid Cooled (DRAFT)

• Sky Scout OPV Mini-Helicopter	• DARPA ANCILLARY

Engine Type / Configuration	V-Twin (60 degree) 4-cycle Supercharged
Bore x Stroke = Displacement	(60mm x 48mm) x 2 = 540cc (16.2 in^3)
Induction / Supercharge	Crankcase / 2:1 / Centrifugal Supercharge
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	50 hp @ 7800 RPM / BMEP = 153 psi
Surface / Volume Ratio	8.76in2/16.2 in^3 = 0.54:1
Fuel Consumption / Cruise	0.48 lbs/hp-hr
Specific Power	25 hp/16.2 in^3 = 1.54 hp/in^3
Specific Weight	25 hp/21.8 lbs = 1.15 hp/lb
Specific Volume	9.3L x 8.2W x 9.1H = 0.396 / 25hp/0.396 = 63hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

Similar in operation to the flat opposed SIO-260F, the even fire 60-degree Turbocharged Injected Vee (TIV-540) is a more compact variation. The primary balance weights are built into the single piece billet crankshaft, while the sleeve valves are phased 180 degrees apart and share the same overlapping crankcase volume. This engine was built for the Boeing RQ-21 Blackjack Navy STUAS aircraft but has been relegated to a low priority now that the DARPA ANCILLARY program has redefined the larger VTOL aircraft.

SIO-356 / 4-Cycle / Supercharged / 42 shp

- DARPA ANCILLARY

Engine Type / Configuration	Flat Opposed Twin (180 degree) Supercharged SV
Bore x Stroke = Displacement	(64.5mm x 54.5mm) x 2 = 712 cc (32.4 in^3)
Induction / Supercharge	Crankcase / 2:1 / Centrifugal Supercharge
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	42 hp @ 6,500 RPM / BMEP = 158 psi
Surface / Volume Ratio	10.12 in^2/ 21.72 in^3 = 1.93 hp/in^3
Fuel Consumption / Cruise	0.45 lbs/hp-hr
Specific Power	42 hp/21.72 in^3 = 0.46:1
Specific Weight	42 hp/22.5 lbs = 1.93 hp/in^3
Specific Volume	8.5L x 15.8W x 6.4H = 0.54 ft^3 / 42/0.54 = 78 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The Supercharged Injected Opposed (SIO-356) was the original heavy fuel engine designed to be a direct replacement for the AR-741 gasoline rotary engine on the Shadow 200. The engine is exceptionally lightweight, being on par with the rotary engine at 23 lbs. The roller bearing crankshaft being a three-piece assembly using a unique tapered polygon press fit geometry. The induction from the crankcase being transferred by the external manifold, thereby increasing the cylinder fin schedule and cooling down to the crankcase. The reed block induction supports the internal 2:1 supercharged delivery ratio. Numerous DARPA/ANCILLARY contractors are adopting this engine for their VTOL aircraft.

AXI-525 / 4-Cycle / 21 shp

- Shadow 200

- Wingtip Vortex Propulsor

Engine Type / Configuration	Axial 3-cylinder / 4-cycle sleeve valve
Bore x Stroke = Displacement	(65.5mm x 52mm) x 3 = 525 cc (32in^3)
Induction / Supercharge	Naturally Aspirated Sleeve Valve
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	21 hp @ 5200 RPM / BMEP = 102 psi
Surface / Volume Ratio	14.96 in^2/31.5 in^3 = 0.475:1
Fuel Consumption / Cruise	0.50 lbs./hp-hr
Specific Power	21hp/31.3in^3 = 0.66 hp/in^3
Specific Weight	21hp/16.2 lbs. = 1.56 hp/lb
Specific Volume	8.5 in diam. x 12.2L = 0.35 ft^3 / 21/0.35 = 57hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

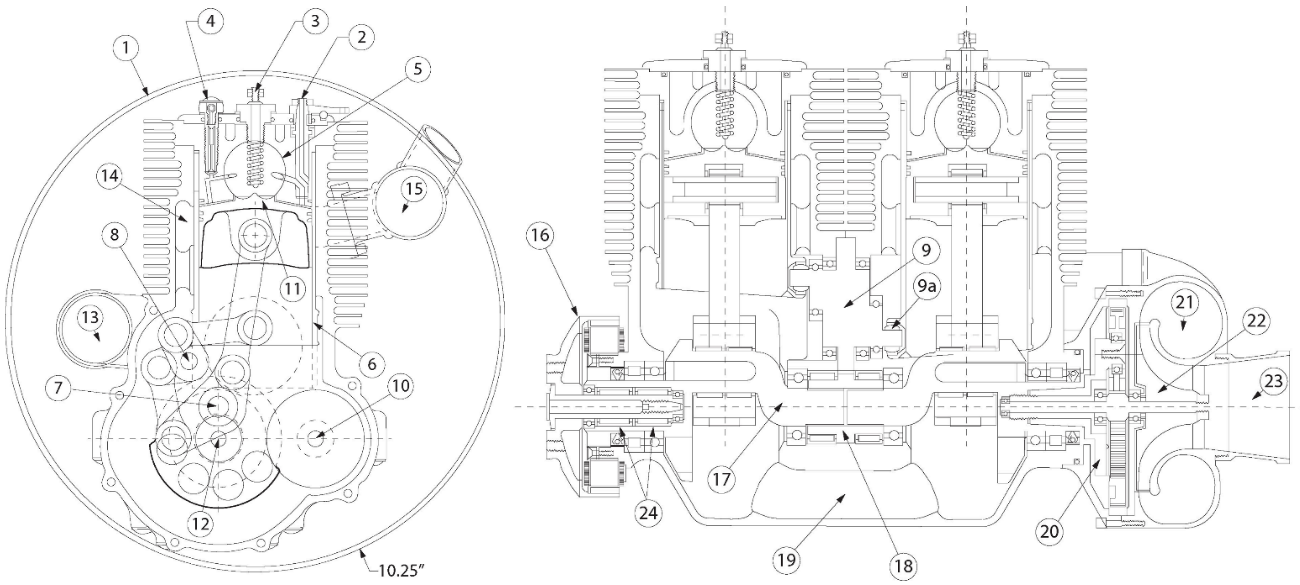
Premise:

The axial 3-cylinder 4-cycle sleeve valve engine was originally intended as an IRAD program aimed at the compact wing tip propulsors installed on the NASA X-57 hybrid aircraft. The 21 hp was to provide constant power generation as well as exceptional aerodynamic cruise efficiency by counter rotating the propellers to the naturally occurring wing tip vortices. This provides a 15~20% boost in direct thrust while providing the essential power generation back to the battery energy storage. The result is a net gain to the commercial EVTOL community exhibiting similar form factor and the need for clean/efficient hybrid propulsion in order to meet FAA requirements.

SIL-282sv / 4-Cycle / Supercharged / 20 shp

"Gemini Range Extender"

(Pat. Pend. 2023)



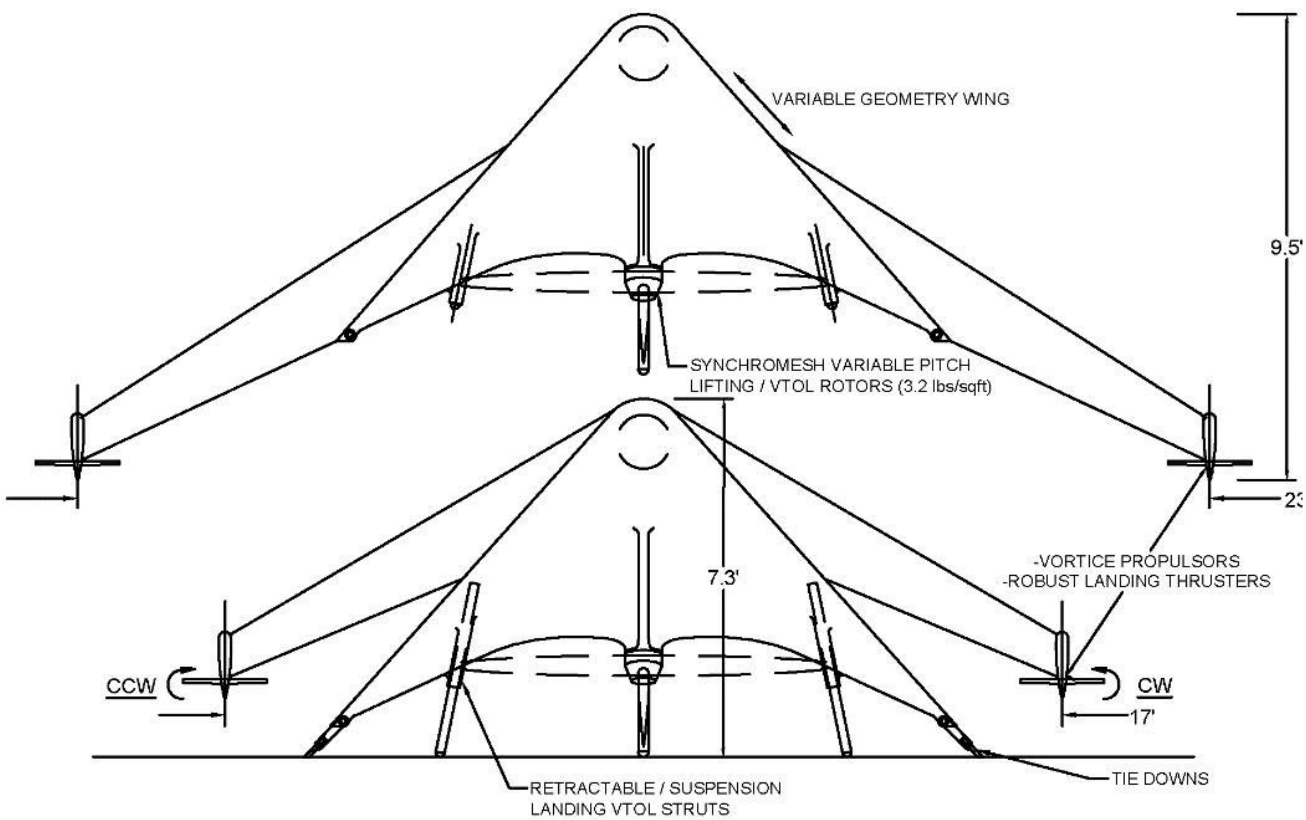
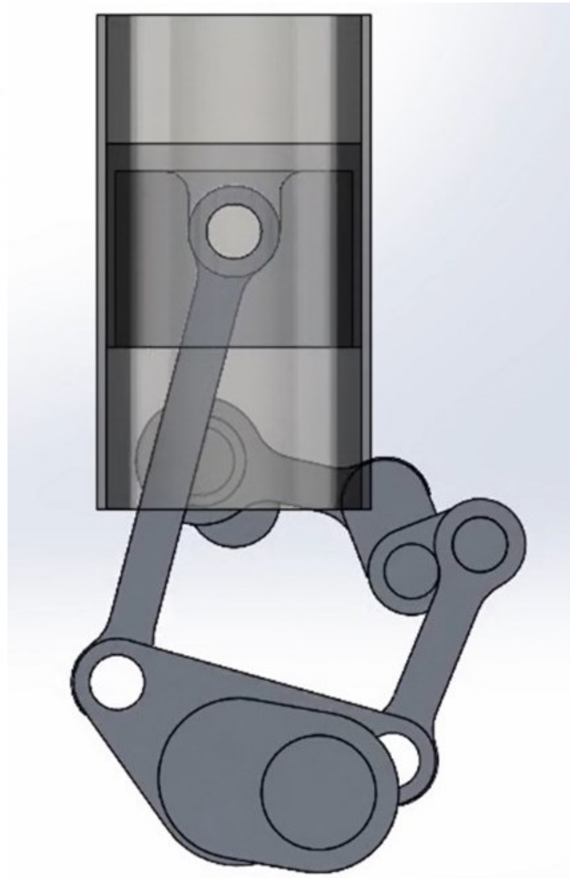
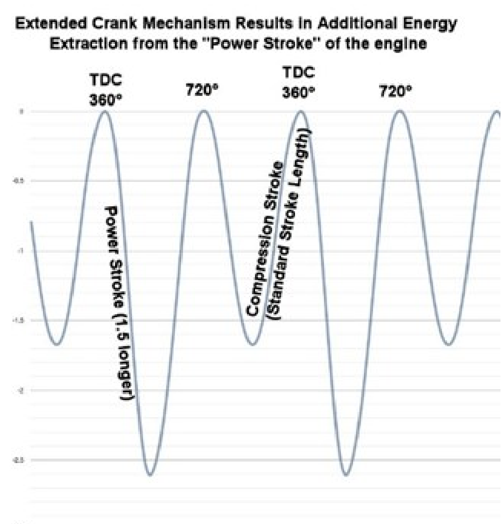


Figure 1- GSE ***VALI*** *Airframe* ***(Pat. Pend. 2023)***

SIL-282sv - Salient Features	
Engine Type	In-Line Even Fire 4-cycle Sleeve Valve
Item #	Description
1	10.25" Diameter Mid-Line / 40hp/ft^3
2	Variable Valve: Compression / Atomizer / Run
3	Catalytic Hot Surface Ignire (CHSI™) (Pat.Pend.)
4	GSE Poppet / Fuel Injector (Pat.Pend.)
5	Lipped Vortex Combustion Chamber (Pat.Pend.)
6	Desmodromic Sleeve Valve
7	Hyper Expansion Crank Linkage (Pat. Pend.)
8	Bellcrank / Linkage (1/2 Speed)
9	Common Sleeve Valve / Crank Linkage Eccentric
10	Balance Shaft 1:1 / Coxail Overdrive Option
11	Displacer Piston / Hyper
12	Primary Crankshaft / Output
13	Common Induction Manifold
14	Inlet Port Belt (3 inlet ports)
15	Exhaust Port / Manifold (2 exhaust ports)
16	1kw Starter / Generator / Drive Coupling
17	Modular Threaded Crankshaft
18	Crankshaft Coupling / Pinion Gear
19	Common Crankcase Transfer Passage
20	Planetary Step-Up (8.2:1) Gearing
21	Centrifugal Induction Schrol
22	Billet Mechanical Impeller / Low Trim Height
23	Intake Velocity Stack
24	One-way Drive Clutch Assembly



SIL-282sv / 4-Cycle / Supercharged (Continued)



- GSE VALI[1] Airframe

Engine Type / Configuration	In-Line Twin / Air-cooled / Supercharged / Sleeve Valve / Hyper Expansion Crank Mechanism™ (Pat. Pend.)
Bore x Stroke = Displacement	(60mm x 50mm) x 2 = 282cc (564cc trapped) (17.21in^3)
Induction / Supercharge	Centrifugal Supercharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	20hp @5,400 RPM / BMEP = 173 psi (Flat Rated to 15,000ft)
Surface / Volume Ratio	8.76 in^2 / 33.8 in^3 = 0..18:1
Fuel Consumption / Cruise	0.42 lbs/hp-hr
Specific Power	20 hp / 17.21 in^3 = 1.16 hp / in^3
Specific Weight	20 hp / 21lbs = 0.95 hp / lb
Specific Volume	12.8L x 9.6H x 7.1W = 40hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 4

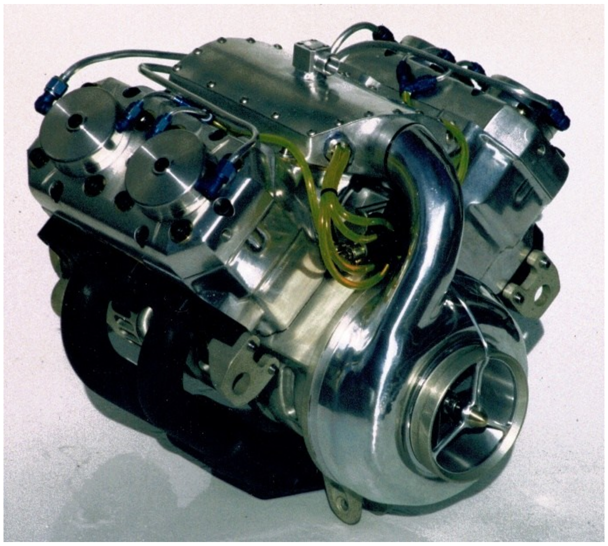
Premise:

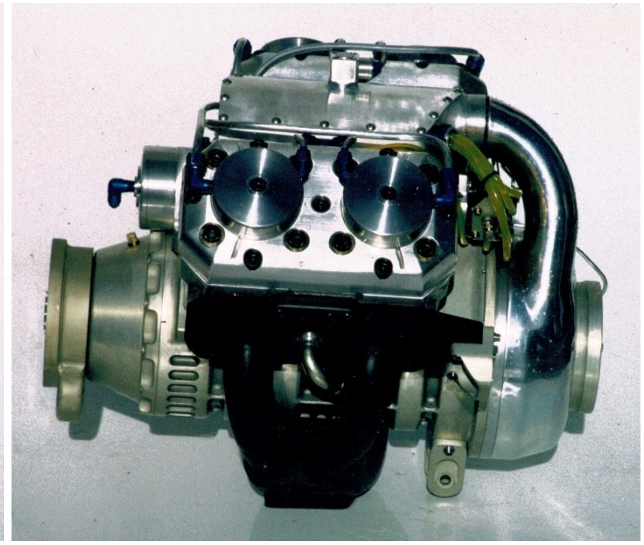
The emerging SIL-282sv supercharged in-line twin cylinder 4-cycle engine represents the pinnacle in thermal efficiency under the ESSP Group II engine categories. The induction system is two stages fitted with a centrifugal supercharger feeding into the common crankcase volume resulting in a 2:1 delivery ratio. The preferred pneumatic injection supports both on demand VTOL takeoff power as well as lean burn part load cruise efficiency; thus, making it a new engine type that is referred to as a “split personality engine™” (SPE™). Gains in thermal efficiency are attributed to the inherently low surface to volume ratio combined with the intermittent “hyper expansion crank mechanism™” power stroke thereby extracting the utmost thermal yield from the fuel. It is anticipated that this large Group II propulsion engine technology may be able to approach a Brake Thermal Efficiency of 40~45%. The high expansion ratio lends itself to maximum efficiency plus significantly reduces the exhaust gas temperatures and exhaust noise.

[1] In Norse mythology, Váli is a son of the god Odin and giantess Rindr. Váli's brothers are Thor, Baldr and Víðarr. When Baldr was killed, Váli killed the person who killed him. He grew to full adulthood in one day. It is unclear if Norse people worshipped Váli as a god or whether he was only a character in the Poetic Edda. He is also the ***god of flight***. Anything that passes through the sky, whether man made or of nature is under his control. To symbolize this his cloak is made of raven feathers that when he spreads his arms looks like wings. Váli is fated to survive Ragnarök.

1.3. Group III Engine Catalog (75~250hp)

SIV-4307 / 2-Cycle / Supercharged / Turbocharged / 72 shp





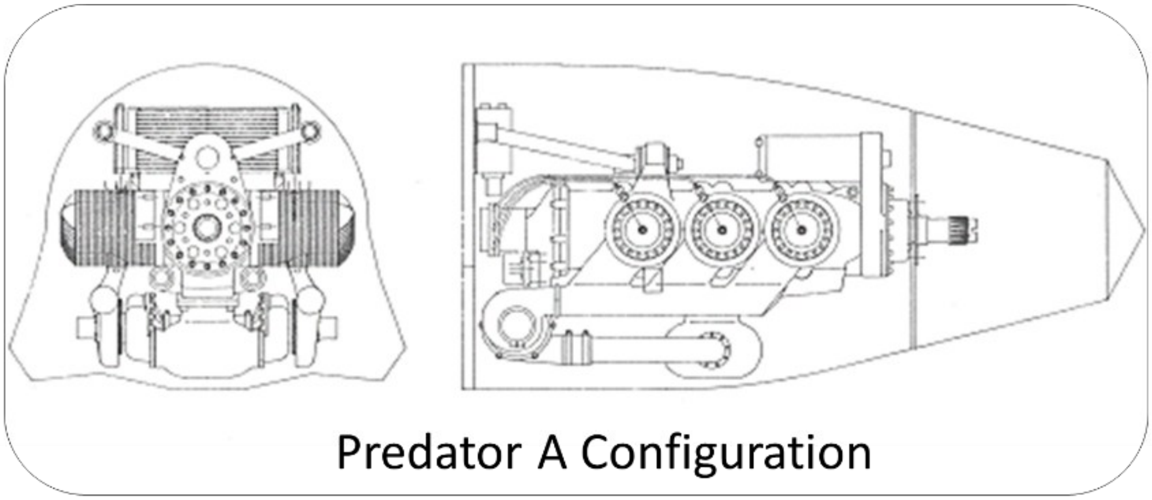
- Joint Tactical UAV

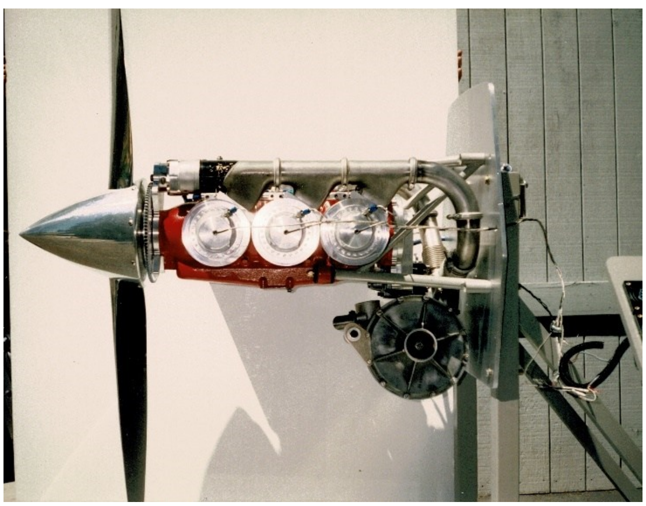
Engine Type / Configuration	V-Four (90 Degree) Supercharged 2-cycle
Bore x Stroke = Displacement	(78mm x 72mm) x 4 = 1,376 cc (82 in^3)
Induction / Supercharge	Centrifugal Supercharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	72 hp @ 4200 RPM / BMEP = 83 psi
Surface / Volume Ratio	29.6 in2/82 in^3 = .361:1
Fuel Consumption / Cruise	0.46 lbs/hp-hr
Specific Power	0.878 hp/in^3
Specific Weight	72hp/84lbs = .86hp/lb
Specific Volume	14.2L x 12.1H x 15.6W = 1.55 ft^3 / 72/1.55 = 46.5hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

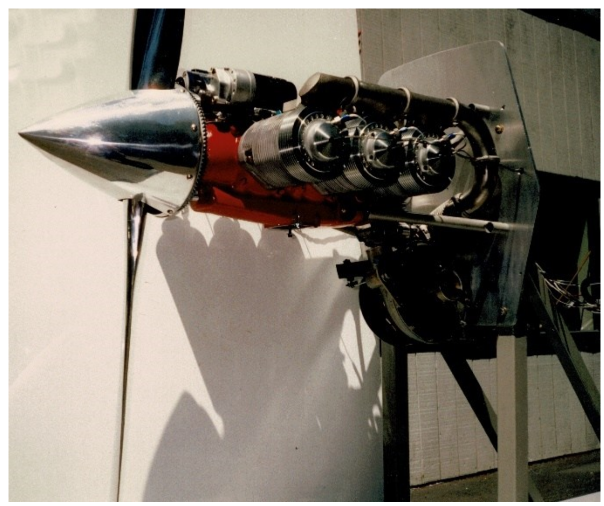
Premise:

The current SIV-4307 was based on the joint tactical HFE requirement in 1996. After demonstrating our high-speed multi-fuel combustion system on a MCOTS engine, the call came for a purpose-built engine in the 60~70 hp range to ensure UAS STOL capability. As a Compression Ignition (CI) engine much time was spent on the robust size of the roller bearing elements to operate at elevated peak pressure. Good fuel consumption was the best trait of the CI variation, whereas the potential to convert to the modern CHSI ignition would significantly improve the power/weight by some 20~25%.

TIO-625 / 2-Cycle / Turbocharged / 125 shp







- Predator A

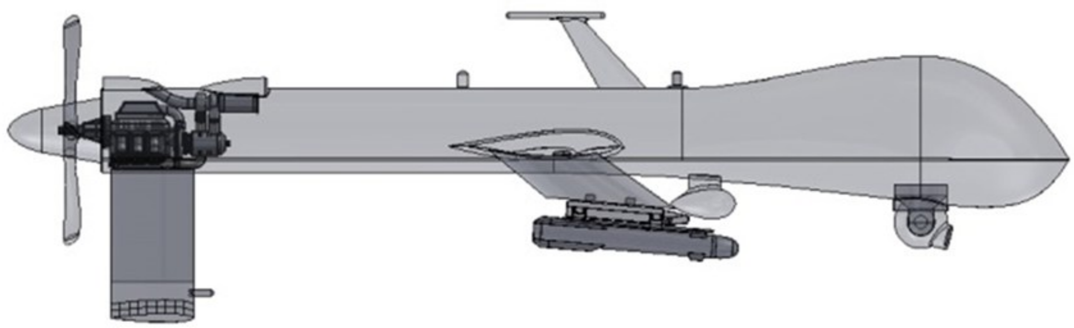
Engine Type / Configuration	Flat-Six (180 degree) Turbocharged 2-cycle
Bore x Stroke = Displacement	(81mm x 79.3mm) x 6 = 2,454 cc (150 in^3)
Induction / Supercharge	Turbocharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	125 hp @ 4,100 RPM / BMEP = 81 psi
Surface / Volume Ratio	47.9in2/149.7in3 = 0.32:1
Fuel Consumption / Cruise	0.44 lbs/hp-hr
Specific Power	125hp/150in^3 = 0.83hp/in^3
Specific Weight	128lbs/125hp = 1.02 lbs/hp
Specific Volume	22.4L x 27.8W x 9.1H = 3.27ft^3 / 125/3.27 = 38hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

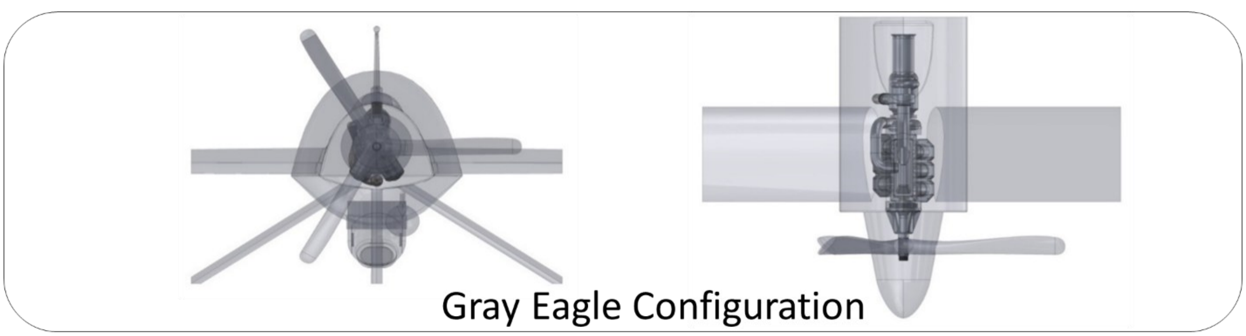
The turbocharged injected opposed flat six-cylinder engine (TIO-625) was an internal GSE IRAD project aimed as a direct replacement to the gasoline Rotax 914 engine used to power the original Predator MQ-1 aircraft. Once the Army bought into the medium endurance aircraft program the Air Force Predator morphed into the Army Grey Eagle UAS. Although GSE TIO-625 engine was presented to General Atomics, the support funding never materialized. The engine is virtually ½ the weight of the competing automotive based TAE-125 diesel engine.

TIV-630H / 2-Cycle / Turbocharged / 196 shp

TIV-630H



Gray Eagle with TIV-630H



Gray Eagle Configuration

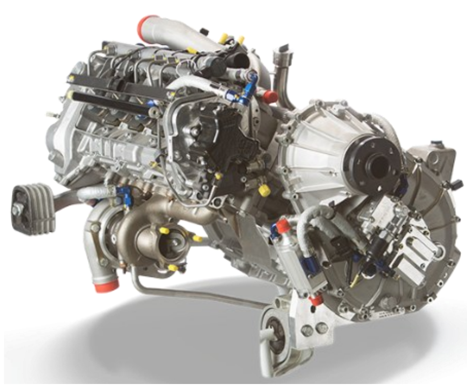
- Gray Eagle UAV

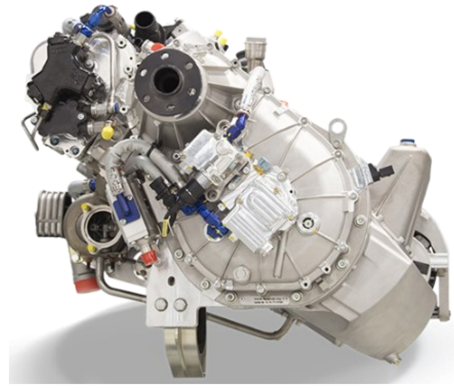
Engine Type / Configuration	V-Six (60 degree/even fire) Hyper-Bar Turbocharged 2-Cycle
Bore x Stroke = Displacement	(92mm x 76mm) x 6 = 3,059cc (186 in^3)
Induction / Supercharge	Hyper-Bar Turbocharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	196 hp @ 4500 RPM / BMEP = 93 psi
Surface / Volume Ratio	61.9in2/186in3 = 0.33:1
Fuel Consumption / Cruise	0.45 lbs/hp-hr
Specific Power	196 hp/186in^3 = 1.05 hp/in^3
Specific Weight	196hp/228lbs = .86 hp/lb
Specific Volume	23.8L x 17.3W x 18.6H = 4.4 ft^3 / 196/4.4= 44.5 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The liquid cooled turbocharged 60-degree Vee even fire six-cylinder engine was the response to the Army Gray Eagle HFE engine replacement under the RASPS program. The major premise being the replacement of the TAE-155 Mercedes Diesel engine due to the recent purchase from AVIC delegation in China. A domestic replacement was sought having high altitude (25,000 ft) and exceptional part load fuel economy were prime concern. The TIV-630H excelled in this competition in terms of power/weight/cost ramifications. Unfortunately, the competition was conducted by Army Ft. Eustis which had little to no Diesel engine expertise and actually requested release certificates to have FEV in Germany do the evaluation. GSE decline.

TAE-155 (Mercedes MCOTS) / 4-Cycle / Turbocharged Diesel / 153 shp





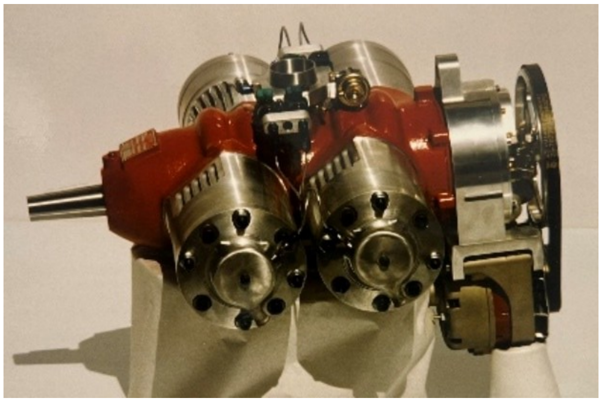
- Gray Eagle

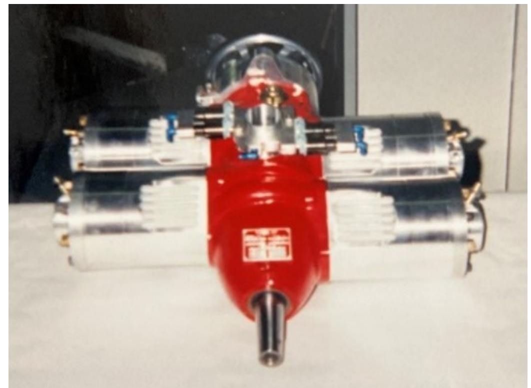
Engine Type / Configuration	In-Line/4-Cylinder/4-Cycle Turbocharged
Bore x Stroke = Displacement	(83mm x 92mm) x 4 = 1,981cc (121.5 in^3)
Induction / Supercharge	Turbocharged
DFI Multi-Fuel System	Bosch High Pressure/Common Rail (23,600 psi)
Heavy Fuel Ignition	N/A
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	153 hp @2500 RPM / BMEP = 392 psi
Surface / Volume Ratio	33.5in^2/121.5in^3 = 0.275:1
Fuel Consumption / Cruise	0.40 lbs/hp-hr
Specific Power	153hp/121.5in^3 = 1.26 hp/in^3
Specific Weight	153hp/344 lbs = 0.45hp/lb
Specific Volume	30.6L x 32.12W x 25.03H = 8.07ft^3/153/8= 18.76 hp/ft^3
Logistical Operating Fuels	(DF-2 and modified JET-A)
HFE Component Maturity Level	TRL = 7

Premise:

The GSE introduction to evaluate the production 2.0-liter TAE-155 engine was by invite from General Atomics looking to replicate and upgrade the engine. The objective was to overcome the shortcomings in the basic design and thereby make a lighter more compact engine with improved performance and durability. The MCOTS design led to a new turbocharger design as well with increased pressure ratio necessary attain the 25.000 ft ceiling altitude. GSE in conjunction with DC Turbo provided a purpose-built dual stage compressor turbocharger with nearly double the pressure ratio at 8:1. The viability of the 2-stage / high pressure ratio (8:1) turbocharger was overlooked for unknown reasons by Army Research Laboratory (ARL). A commercial variant is still under GSE / IRAD development.

SIO-425 / 4-Cycle / Supercharged / 105 shp





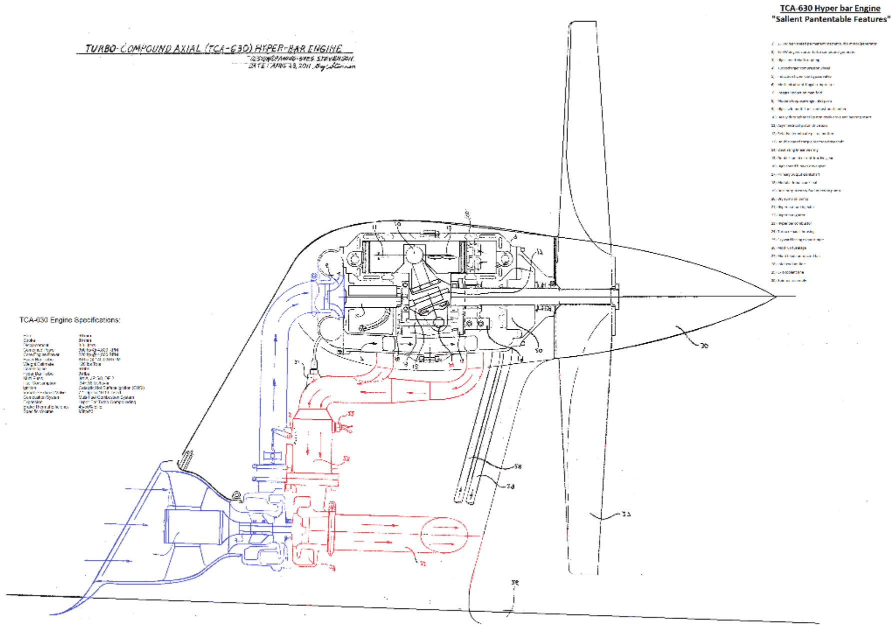
- NASA GAP/CAN Propulsion
- JT UAV Progrom

Engine Type / Configuration	Flat Four (180 degree) sleeve valve 4cycle
Bore x Stroke = Displacement	(80mm x 79.3mm) x 4 = 1,594cc / 95.6 in^3
Induction / Supercharge	Naturally Aspirated
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	105 hp @ 4,100 RPM / BMEP = 212 psi
Surface / Volume Ratio	31.16 in^2/95.6 in^3 = 0.32:1
Fuel Consumption / Cruise	0.41 lbs/hp-hr
Specific Power	105hp/95.6in^3 = 1.098 hp/in^3
Specific Weight	105hp/85 lbs = 1.26 hp/lb
Specific Volume	15.6L x 27.8W x 9.1H = 2.28 ft^3 / 105/2.28 = 46 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The naturally aspirated injected flat 4 cylinder opposed (SIO-425) engine can be described as an exceptionally lightweight 4-cycle sleeve valve engine intended for dual use in both the military and commercial marketplace. It is perhaps the classic example of doing more with less engine bulk and weight while exhibiting exceptional thermal efficiency. This IRAD design was intended to compete directly with the Light Sport Aircraft engine market that is now currently dominated by the geared Rotax 914 engine. This very unassuming engine has 30% less bulk and weight by comparison to the Rotax 914, while having exceptional trapping efficiency that enables direct propeller drive.

TCA-630H / 2-Cycle / Hyper-Bar Compound Turbocharged / 175 shp



- Lockheed MQ-X

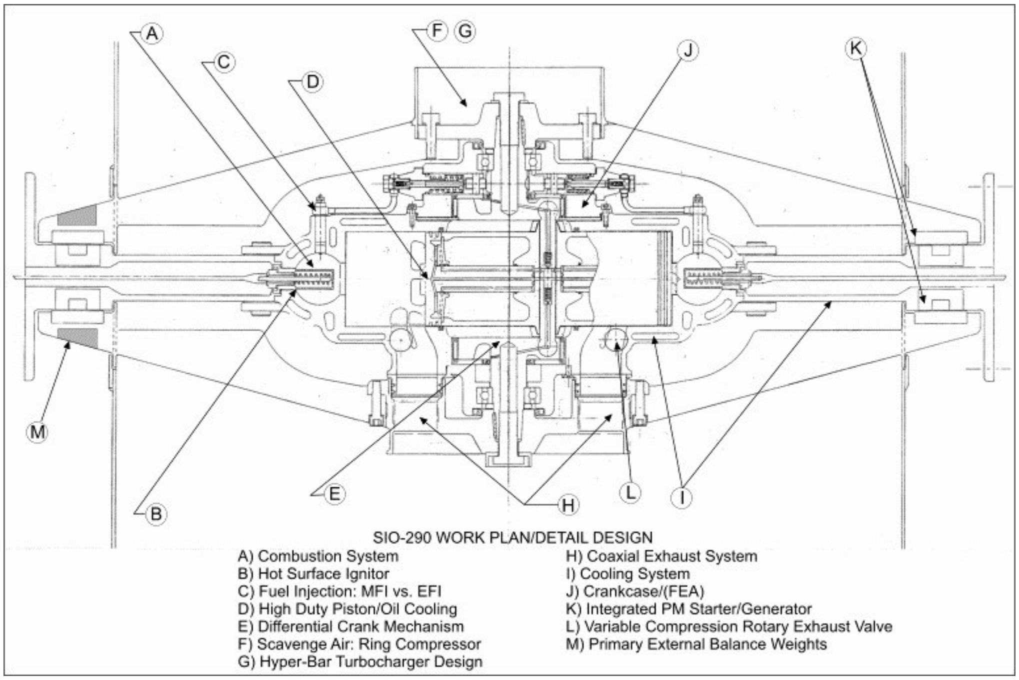
Engine Type / Configuration	Axial opposed cylinder / even fire supercharged six
Bore x Stroke = Displacement	(92mm x 76.2mm) x 6 = 3,059 cc (186 in^3)
Induction / Supercharge	Hyper-Bar Turbocharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	175 hp @ 3,600 RPM / BMEP = 110 psi
Surface / Volume Ratio	0.33:1
Fuel Consumption / Cruise	0.45 lbs/hp=hr
Specific Power	175hp/186 in^3 = .94hp/in^3
Specific Weight	175hp/108lbs = 1.62 hp/lb
Specific Volume	12.8 dia x 21.5L = 1.6ft^3 / 175/1.6 = 109hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

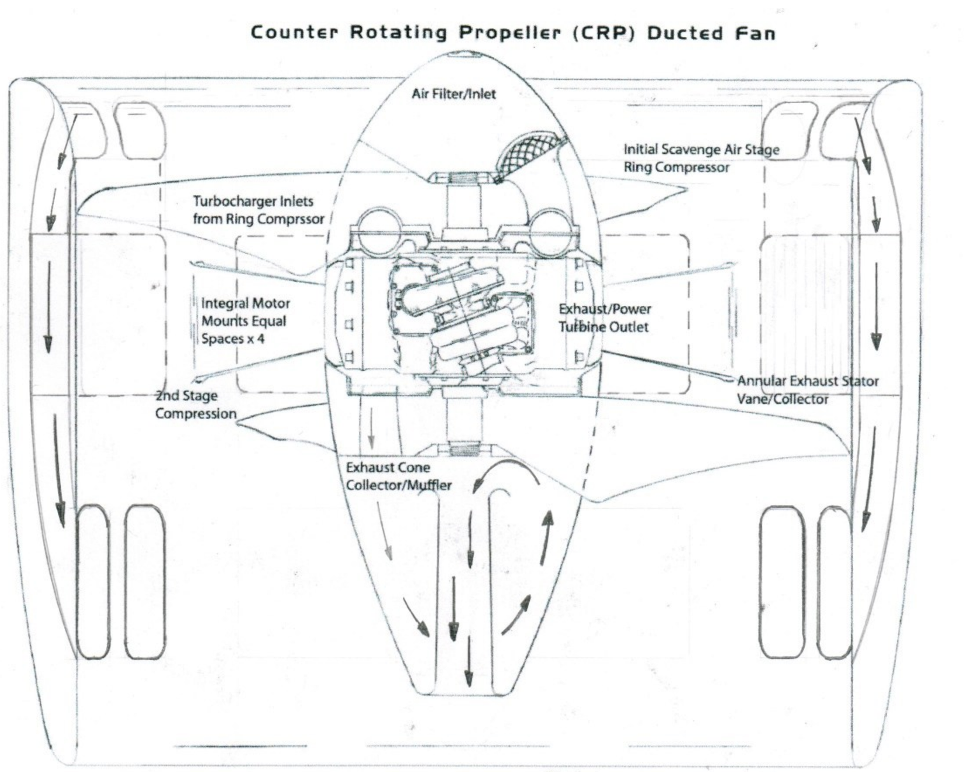
Premise:

The turbocharged compound axial 630 engine was an advanced combine cycle engine study based on the industry desire to marry the virtues of the turbine and piston engine together. (See illustration above the engine specification table). An innovative breakthrough in the axial Z-crank mechanism resulted in uniform piston accelerations while providing the torque reaction through the lemniscate pin geometry. The torque reaction being a double speed eccentric proportion to the Z-crank angle while also providing a robust high speed quill drive for the centrifugal supercharger. The hyper-bar turbocharger assembly being imbedded in the root of the pylon mount with the fuel driven combustor built into the manifold. Perhaps the closets example of having the frontal area and compactness of the gas turbine, while retaining the part load fuel economy of the Diesel.

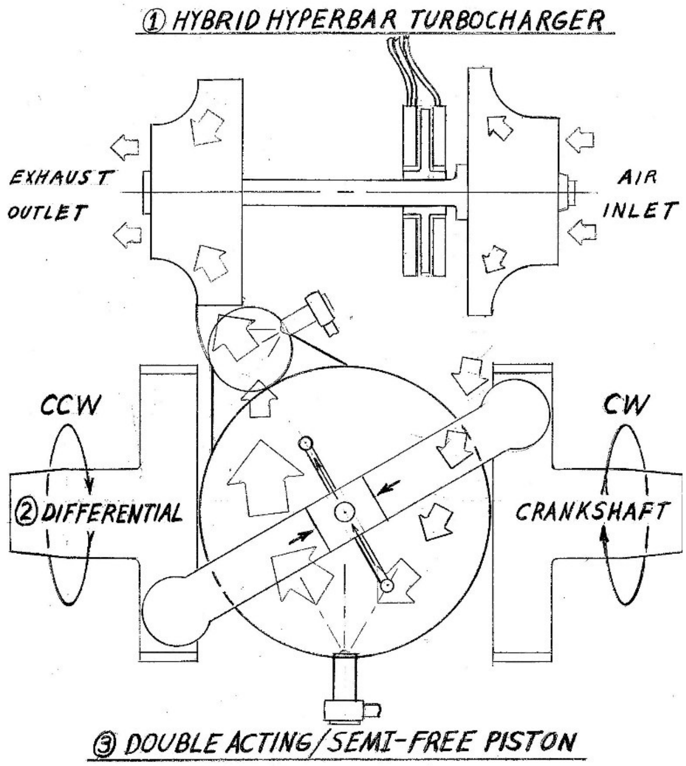
TCIO-246 / 2-Cycle / Semi Free Piston Contra-Rotating Propulsor (SFP/CRP) / 258shp

A Scalable Semi-Free Piston Contra-Rotating Propulsor Ducted Fan





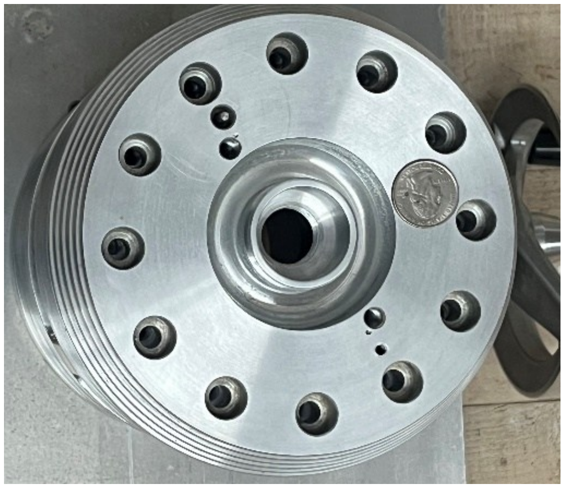
TCIO-246 / 2-Cycle / SFP/CRP / 258shp (continued)

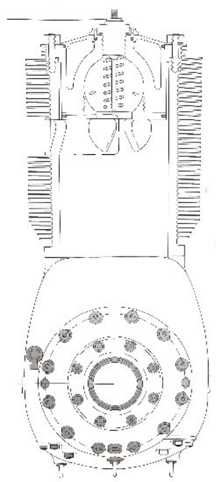


Engine Type / Configuration	Semi-Free Piston Contra Rotating Propulsor
Bore x Stroke = Displacement	(4.09 in. x 3.50 in.) x 2 = 92 in^3
Induction / Supercharge	Hyper-Bar Turbo
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	258 hp @ 6,000 rpm / 220 psi
Surface / Volume Ratio	0.289:1
Fuel Consumption / Cruise	0.36 lbs./hp-hr.
Specific Power	2.83 hp/in^3
Specific Weight	0.52 lbs./hp
Specific Volume	98 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

Premise:

TIL-360 / 4-Cycle / Turbocharged / 190 shp






Engine Type / Configuration	In-Line 3-cylinder Turbocharged 4-cycle sleeve valve
Bore x Stroke = Displacement	(104mm x 115mm) x 3 = 2,931cc (178.9 in^3)
Induction / Supercharge	Turbocharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	190 hp @ 2,800 RPM / BMEP = 300 psi
Surface / Volume Ratio	39.5in2/178.9in3 = 0.22:1
Fuel Consumption / Cruise	0.34 lbs/hp-hr
Specific Power	190hp / 178.9in3 = 1.06 hp/in3
Specific Weight	190hp / 154lbs = 1.23 hp/lb
Specific Volume	31.8L x 12.4W x 28.8H = 6.57ft^3 / 190/6.53= 29 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL-5

TIL-360 / 4-Cycle / Turbocharged / 190 shp (continued)

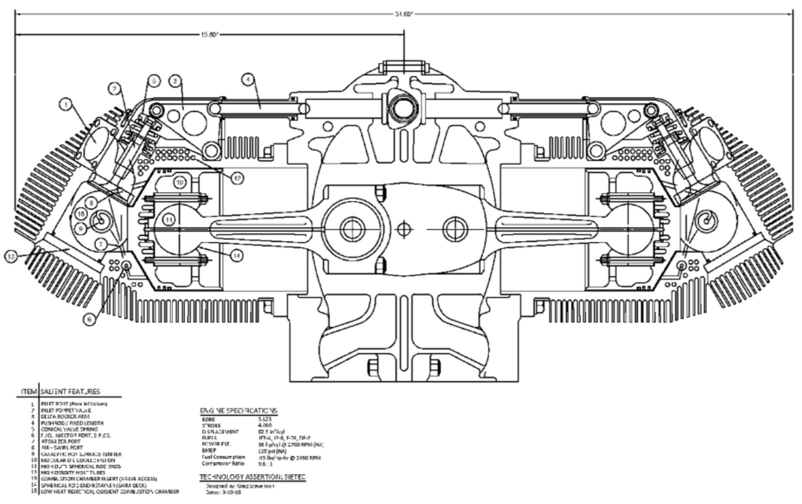
Premise:

The turbocharged in-line TIL-360 is a 4-cycle sleeve valve engine with approximately a three-liter displacement yielding 190 shp. The design premise being an attractive direct drive turbocharged 4-cycle engine to compete with the TAE-155 on the Grey Eagle or the Austro 170 Mercedes Diesel on the Boeing twin engine Orion UAV. Both foreign Aero Diesel engines being owned by AVIC China. Unlike the automotive based Mercedes Diesel engines being limited to 2-liter displacement due to strict OEM tariffs in Germany, the preferred GSE TIL-360 Aircraft sleeve valve engine represents a lighter more compact solution (30% weight improvement {344 lbs. vs 203 lbs.}) while greatly extending the durability. It should also be noted that single cylinder testing of this concept has demonstrated excellent part load fuel economy down to 0.34 lbs./hp-hr[2]. The Orion UAS is the only domestic UAS that truly can compete with the Russian Altius UAS for range and endurance; therefore, if it returns to service, the TIL-360 would be a great upgrade to its powerplant as it would increase the range and endurance even further than it currently is and provide additional payload weight.

[2] (Sir Harry R. Ricardo, 1953 (Reprinted 1962)) Page 337.

1.4. Group IV Engine Catalog (500~900hp)

GSIO-330 / 2-Cycle Opposed 6 / Supercharged / 320 shp



- Retrofit Conversion for Lycoming Engine

Engine Type / Configuration	Flat opposed 6 / 2-Cycle Geared/Supercharged
Bore x Stroke = Displacement	(108mm x 98.4mm) x 6 = 5,408 cc / 330 in^3
Induction / Supercharge	Supercharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	320 hp @ 3,400 RPM / BMEP = 113 psi
Surface / Volume Ratio	85.2 in^2/ 330 in^3 = 0.258:1
Fuel Consumption / Cruise	0.42 lbs/hp-hr
Specific Power	320 hp/330in^3 = 0.97 hp/in^3
Specific Weight	320 hp/410 lbs = 0.78 hp/lb
Specific Volume	42.2L x 32.8W x 21.5H = 18.9 ft^3/320/18.9 = 16.9 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

Premise:

This MCOTS flat opposed six-cylinder engine project was part of a NASA study to convert existing production piston aircraft engine designs. The original geared injected supercharged opposed (GSIO – 330) was based on a popular Lycoming engine. The major conversion being focused on the top end piston/cylinder block assembly for dedicated liquid cooling and engine rigidity. The geared centrifugal supercharger being ideal for 2-cycle scavenge air and the planetary reduction drive enabling the engine the opportunity to make peak power by operating at high speeds. This IRAD project has been reviewed by both Lycoming as well as NASA in terms of an economical technology demonstrator. It also represents a low-cost alternative to Semi-Nomad engine concept with supporting analysis located in the appendix of this document. The real attraction may be the low-cost entry to a production viable (LCAAT) propulsor with a multi-blade ducted fan…

TCIO-1255 / 2-Cycle Opposed 12 / Turbo-Compounded / 900 shp

Engine Type / Configuration	Flat opposed 12/ 2-cycle electrified turbo-compound
Bore x Stroke = Displacement	(98.5mm x 115mm) x 12 = 10,576 cc (641in^3)
Induction / Supercharge	Electrified Turbo-Compound
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	900 hp @ 3600 RPM / BMEP = 154 psi
Surface / Volume Ratio	141.5in^2/641in^3 = 0.22:1
Fuel Consumption / Cruise	0.34 lbs/hp-hr
Specific Power	900hp / 641in^3 = 1.4 hp/in^3
Specific Weight	900hp / 648 lbs = 1.39 hp/lb
Specific Volume	49.3L x 32.8W x 21.6H = 20.4 / 900/20.4 = 44 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 6

Premise:

The TCIO-1255 is GSE's most ambitious combined cycle engine to date. This quarter scale Napier Nomad could double the range and endurance of the MQ-9 Reaper. The modern-day electrified version of the Nomad II being the CHSI™ ignition that overcomes the cold start issue as well as the electrified turbo-compounding thereby eliminating the complex mechanical gearing arrangement between the turbine and the crankshaft. The design premise being a lightweight coplanar liquid cooled cylinder block arrangement with exceptionally high structural efficiency with direct tie rods that sandwich the magnesium crankcase. The modern pneumatic injection and CHSI ignition enable the engine to start from cold just utilizing the energized single stage turbo-compressor thereby dispensing with redundant positive displacement blower. The second stage is by means of conventional MCOTS turbochargers which feed into the combustor of the final blow down exhaust turbine thereby extracting the utmost thermal yield from the fuel for best part load efficiency. The high firing frequency provides a power pulse every 30 degrees of crank rotation and is most suitable for direct propeller drive on fixed wing and/or gear reduction drive as required on rotary wing aircraft.

Red V-12 MCOTS / 4-Cycle V-12 / Dual Turbocharged / 500 shp

•

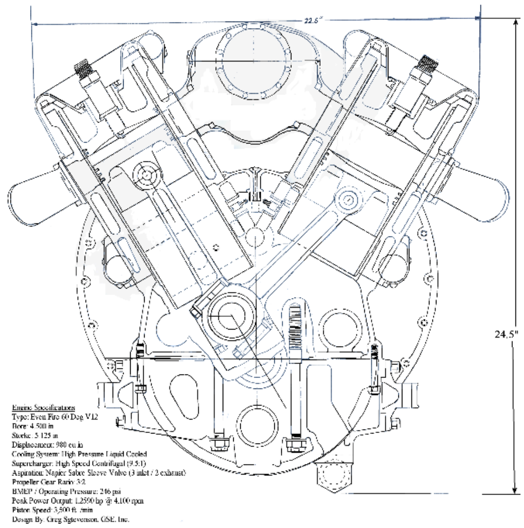
Engine Type / Configuration	V-12 (60 degree) 4-cycle Turbocharged
Bore x Stroke = Displacement	(86mm x 88mm) x 12 = 6,100 cc (372 in^3)
Induction / Supercharge	Dual Turbocharged
DFI Multi-Fuel System	Bosch high pressure common rail (23,206 psi)
Heavy Fuel Ignition	Compression Ignition (CI) 18:1
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	500 hp @3200 RPM / BMEP = 332 psi
Surface / Volume Ratio	108 in^2/372in^3 = .29:1
Fuel Consumption / Cruise	0.35 lbs/hp-hr
Specific Power	500hp/372in^3 = 1.34 hp/in^3
Specific Weight	500hp/800 bs = 0.625 hp/lb
Specific Volume	33.26L x 44.3W x 27.44 H =23 ft3/500/23.4 = 21hp/ft3
Logistical Operating Fuels	(Diesel #2 and modified Jet-A)
HFE Component Maturity Level	TRL = 7

Premise:

The GSE introduction to the RED V-12 has been through private parties integrating this engine into both new and production-based aircraft. Namely the laminar flow OTTO Celera 500L aircraft aimed at high efficiency as well as the Ampaire Cessna Caravan aircraft, both having the objective of operating on unleaded transport turbine fuels with the utmost efficiency. The basic automotive based engine design being constrained by the multi-fuel characteristics of variable viscosity, lubricity, and cetane. The most limiting factor is this engine development was shared originally by the Russian designers developing the ALTIUS UAV having 50 plus hours of endurance.

GSIV-980 / 4-Cycle V-12 / Supercharged / 1,250 shp

GSIV-980 Semi-Saber V-12 Supercharged Sleeve Valve Engine



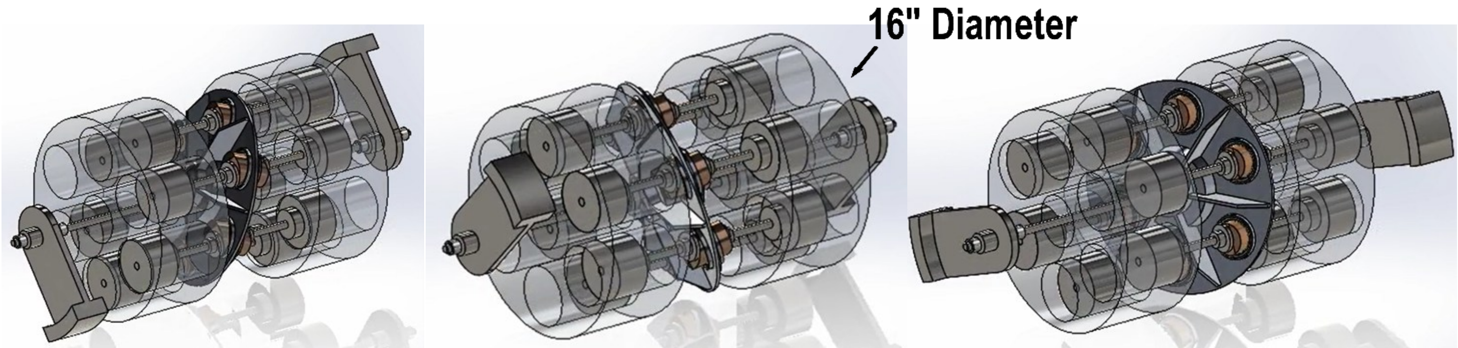
- Reaper

Engine Type / Configuration	V-12 (60 degree) 4-cycle Supercharged Sleeve Valve
Bore x Stroke = Displacement	(114.3mm x 130mm) x 12 = 16,007 cc (980 in^3)
Induction / Supercharge	Compound Differential Centrifugal Supercharged
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	1250hp @4,100 RPM / BMEP = 246 psi
Surface / Volume Ratio	$15.9in^2/81.3in^3$ = .195:1
Fuel Consumption / Cruise	0.34 lbs/hp-hr
Specific Power	1250 hp/980 in^3 = 1.275 hp/in^3
Specific Weight	1250 hp/638 lbs = 1.96 hp/lb
Specific Volume	42L x 22.5W x 24.5H = 13.4 ft^3/1250/13.4 = 93.3 hp/in^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 5

Premise:

The GSE IRAD works on the high powered supercharged (60 degree) V-twelve geared (GSIV-980) engine is the 1 MW class of hybrid power needed for most EVTOL candidates now beginning to adopt the hybrid propulsion architecture. The even fire liquid cooled sleeve valve engine is exceptionally compact and in fact fits well with the cowling of most turbine-based aircraft engines. The long stroke to bore relation results in low surface to volume ratio for best-in-class fuel consumption. The durability being enhanced by the desmodromic sleeve valve assembly driven by a common cross gear quill shaft located down the middle of the Vee-cylinder bank geometry. Although in an early stage, there is no shortage of commercial applications with current production aircraft as well as the emerging EVTOL category of aircraft looking for a FAA certification path. The production short block assemblies based on the Allision V-12 heritage.

AXI-1255 / 2-Cycle Axial 12 / Hyper-Bar Turbo-Compound / 900 shp



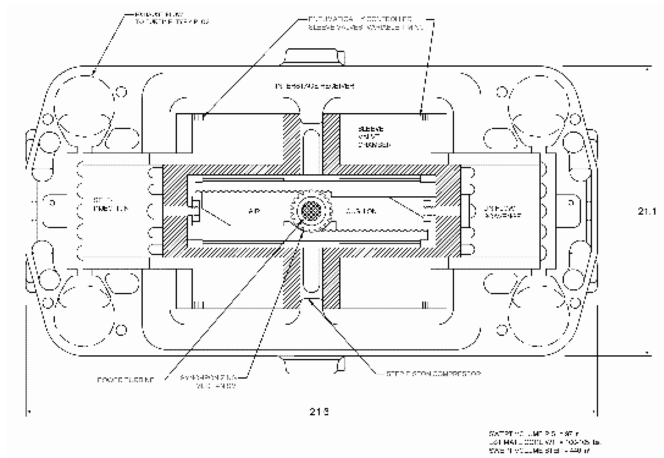
Engine Type / Configuration	Axial 12-cylinder Electrified Turbo-Compound Engine
Bore x Stroke = Displacement	(114.3mm x 130mm) X 12 = 10,515cc (641 in^3)
Induction / Supercharge	Electrified Hyper-bar turbo-compound cycle
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	900 hp @ 3600 RPM / BMEP = 154 psi
Surface / Volume Ratio	0.22:1
Fuel Consumption / Cruise	0.36 lbs/hp-hr
Specific Power	900hp/641in^3 = 1.4hp/in^3
Specific Weight	900hp/372 lbs = 2.42 hp/lb
Specific Volume	16 in dia. X 40 L = 6.18 ft^3 / 900/6.18 = 145 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 4

Premise:

The last of the axial engines to be investigated is also aimed at the emerging commercial EVTOL market. In particular, the dual use JOBY S-4 aircraft currently under the Air Force Agility Prime program. Although the DoD has adopted the current Bell Tilt rotor concept as defined by the classic V-22 Osprey but more recently even the Blackhawk replacement in the Bell/Valore 280 tilt rotor. The smaller Joby S-4 has preference for smaller short hops under the Agility prime program. However, the Air Force needs in terms of range and payload greatly exceed the current all electric Joby S-4 capability. Therefore, the larger axial parallel hybrid engine is being designed with the intent to replace wingtip propulsors, thereby opening cabin space for necessary payload and range equivalence.

RAC / NASA /

Free Piston Turbine



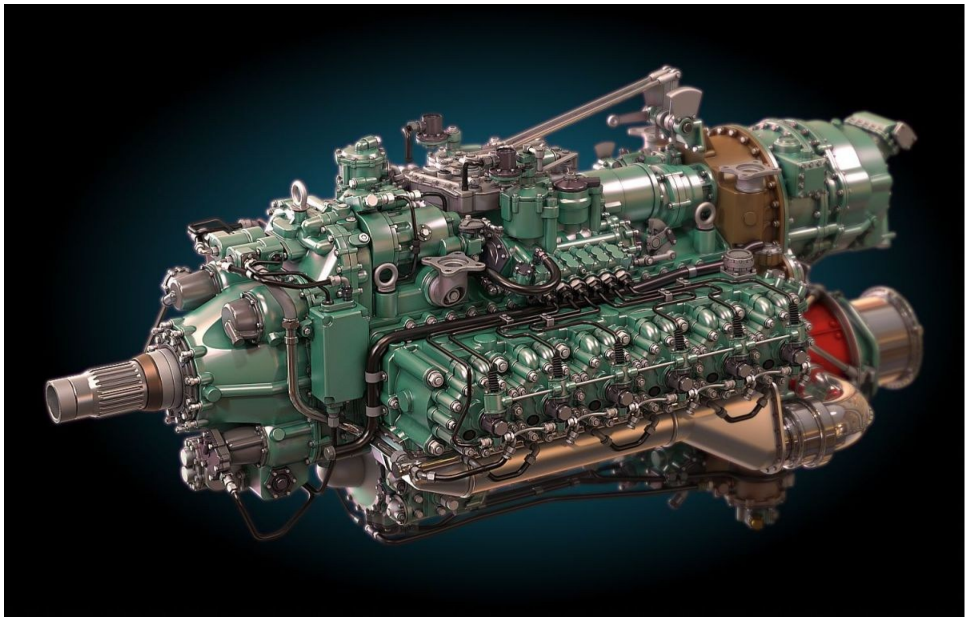
Engine Type / Configuration	Opposed piston Uniflow Sleeve Valve Gasifier
Bore x Stroke = Displacement	(98.4mm x 105mm) X 2 = 1,597 cc / 97 in^3
Induction / Supercharge	
DFI Multi-Fuel System	Pneumatic Self Injection
Heavy Fuel Ignition	CHSI™
Multi-Fuel Combustion System	Modern Hybrid DI / IDI / M-System
Power Output / BMEP	300 hp @3600 CPM / BMEP = 340 psi
Surface / Volume Ratio	23.6in^2/97.6in^3 = 0.24:1
Fuel Consumption / Cruise	.48 lbs/hp-hr Gasifier + turbine @ 600 shp
Specific Power	300 hp/97 in^3 = 3.09 hp/in^3
Specific Weight	300hp/91 lbs = 3.3 hp/lb
Specific Volume	12.9L x 21.5W x 12.1H = 1.95 ft^3/300/1.95=154 hp/ft^3
Logistical Operating Fuels	DLA Inventory: (JP-5/JP-8/Jet-A/F-24/F-76/Bio-Diesel)
HFE Component Maturity Level	TRL = 4

Premise:

Small gas turbines much below 2,500 shp have suffered due to the high leakage and limited pressure ratios attainable from turbine compressors. Most attempts to raise the efficiency of small gas turbines have been some form of exhaust gas recuperation, but these generally suffer in bulk and weight while placing higher operating speeds and centrifugal loading on the power turbine. Alternatively, GSE has been promoting the "Free Piston/Topping Cycle" to energize the compressed gases up stream of the turbine combustor. A two phased compression system can greatly improve the pressure ratio from 8:1 to beyond 40~50:1 for a given turbine application. The primary technical challenge of the gasifier being the fuel injection timing and asymmetrical blow down timing to harness the on-demand power from the turbine. The innovative piston geometry of self-injection technology is considered key to making this topping cycle the most practical and scalable for turbines down to Group II category. The free piston uniflow 2-cycle gasifier illustrated here was sized for the Honeywell TPE-331 turboprop that powers the Air Force MQ-9 Reaper Group IV UAS.

Theoretical Semi-Nomad Flat Six Cylinder Analysis

"Low Cost Attritable Aircraft Technology (LCAAT)"



Premise:

The Air Force "Low Cost Attritable Aircraft Technology" (LCAAT) program is still in need of a lower cost prime mover at about half the part load fuel burn in order to achieve the 1,500 nautical mile range expectation. The theoretical analysis provided here was privately examined by the author in looking for a future compound cycle engine applicable to both the commercial aviation sector as well as a possible high speed sprint engine for future LCAAT application. The military variant of the flat six Semi-Nomad would have an improved power to weight ration approaching 2:1 due to the electrified turbo-compound coupling combined with the modern CHSI ignition and nearly double the operation speed. This would lend itself to a simple direct drive multi-blade ducted fan delivering up to 5 lbs of thrust / hp. The blow down energy from the hyper-bar turbine exhaust would also contribute to the net thrust while providing full expansion thereby extracting the utmost thermal yield. The muti-blade fan would be pitched to provide upwards of 2,500 lbs of thrust at the prescribed 0.85 Mach in order to achieve speed parity with fighter jets while exhibiting over double the range and endurance for a given fuel load.

The joint analysis is baselining commercial variant of the so-called Semi-Nomad 6-cylinder engine and is provided under "Future Possibilities" for both commercial as well as military aspirations. The performance and cost estimate is virtually ½ the fuel burn and production cost for double the range and endurance…

See LCAAT – TCIO-246 Performance Data (Section 3.11 – Page 29) in "Discussions" segment. Section 3.12 – Page 32 contains the entire article entitled "Napier Nomad II Aircraft Engine Performance Verification Using Numerical Modeling" by J. David Kirk (included here with authors permission as it was published 1 April 2021 on EngineHistory.Org).

2. CONCLUSIONS

The fuel characteristics of turbine transport fuels are widely different from closely regulated commercial pump Diesel fuels that dictate the need for a proper multi-fuel injection/combustion system technology. The proof is in the number of failed attempts to introduce MCOTS production Diesel engines that rely on production Bosch fuel injection technologies stemming from communist China. Modern high pressure electronic common rail fuel injection systems are especially sensitive to fuel viscosity, lubricity and cetane values that results in derating these engines by some 10~15% with an integrated power density of approximately 3lbs/hp. This relaxed power density may be accommodated by larger group III/IV UAS such as the Air Force Orion and/or the Army Grey Eagle UAS, but clearly unacceptable for smaller group I/II UAS designed around gasoline engines of 1 lb/hp power densities.

The square/cube law in scaling these engines down reaches an early point of diminishing returns whereby the internal leakage and heat losses overcome the practical limit of compression ignition. Commercial Diesel engine scale limited to 70mm (2.75-inch bore) range and just 4 hp @ 3600 RPM.

Breakthrough self-injection technology has proven to scale down to just 25mm (1.0-inch bore) while maintaining an engine bulk and weight competitive to spark ignited gasoline engines while retaining the lean burn part load efficiency of the Diesel cycle. The application of this multi-fuel injection/combustion process has now been demonstrated on both 2-cycle as well as 4-cycle engines ranging from 1 to 5 inch bore range. Naturally aspirated engines with tuned exhaust can achieve up to 36% BTE while full expansion electrified turbo compound machines can achieve up to 45% BTE. The real advantage for aircraft use is numerous:

- The use of logistically available unleaded Jet-A transport turbine fuels.
- The elimination of electrical interference from high tension electrical ignition.
- Compact, robust two phased mechanical fuel injection system immune to EMP burst.
- A passive pneumatic self-injection system utilizes the stored energy of internal gas dynamics. (i.e.: Pneumatic cylinder gas pressure/temperature proportionate to engine speed/load.)
- Modified M-system combustion chamber introduces the bulk of the fuel prior to pilot injection/combustion resulting smooth combustion.
- Modern Catalytic Hot Surface Ignition (CHSI) is always well above self-ignition temperature thereby immune to fuel cetane values much like the modern gas turbine.
- Passive pneumatic injection is insensitive to jet fuel variations in fuel viscosity or lubricity, while the “Fuel Deposit on the Wall” method of injection controls fuel heat release/pressure trace.
- The evaporative fuel deposit on the wall of the combustion chamber normalizes the heat release and favorable combustion trace essential for lightweight/durable engine. (Peak/Mean PSI 6:1)
- New composite HFE propulsion requirements stemming from current DARPA ANCILLARY mission profile has split performance characteristics, namely 2X power for VTOL and 1/10th power for cruise efficiency. Innovative variable swirl ratio cut off valve being introduced. (See Figures 15-17)

Unlike the modern (SI) or (CI) engine technologies, the recently discovered CHSI multi-fuel combustion system is scalable across all UAS Groups I ~ IV without compromise to reliable cold start, multi-fuel combustion, and/or high-altitude lapse rate. This is primarily due to the robust pneumatic self-injection and CHSI heavy ignition system enabling complete freedom of compression ratio and subsequent degree of on demand supercharge.

2.1. Recommendation for phase III production tooling

Robert Bosch has captured the current Diesel engine manufactures for delivering fuel systems based on premium commercial pump Diesel fuels. Worldwide fuel logistics dictate the use of kerosene-based transport fuels. Self-injection technology has been proven on engines from 1 to 5 inch bore range. This includes all the details in the mechanical rotary plunger fuel injection pump and low-pressure poppet type injector nozzle. The production tooling being a modest scaling exercise and does not require the long process of tungsten carbide materials to withstand the low lubricity jet fuels. Conversely the parts do not require the numerous stages of heat treatment and precision lapping, but rather slip fits in the range of .0002/.0005 are normally exercised from simple honing process. The domestic USA needs a home-grown solution for production of a military grade high speed heavy fuel production engine series.

From a commercialization standpoint, these proven production methods and tooling can be licensed to companies like Stihl that has taken a major hit from the elimination of small (below 25 hp) utility spark ignition (SI) engine production under the California SORE program. Likewise, the 5-billion-dollar EVTOL industry is now taking a hard look at series hybrid solutions for both Turbine and ICE versions pending. It should be noted that the synergy gained by introducing multi-fuel combustion technology is very much in-line with what is needed to operate on future transport fuels such as LNG and/or liquid Hydrogen. Et zero emissions being the goal, which also entertains recently demonstrated carbon negative aspects of DME pilot/propane fumigation. No shortage of possibilities here, just the need to demonstrate through collaborative efforts with Air force Agility Prime now funding the EVTOL "Race to Certification" in conjunction with NASA goals of net zero emission aviation propulsion technologies.

Perhaps the most important growth potential of the technology for DoD to consider is the looming challenge of energy needs faced by expeditionary forces mounting in the Indio-Pacific. Biodiesel fuels now being extracted from marine plant growth such as algae and/or seaweed is full of potential with early demonstration in expensive omnivorous fuel burning gas turbines. By contrast over double the efficiency can be harnessed by scaling up the self-injection technology for large stationary Diesel engines. Even better would be the introduction to the future 2050 MTU/Rolls Royce turbine topping cycle approaching 50:1 pressure ratio. This scaling up would improve over 30% efficiency, while the high-speed nature is exactly what is necessary to support the gas flow through turbine engine design under long range cruise. No shortage of possibilities, just need phase II experiment and phase III tooling to transition to the commercial fleet.

3. DATA RIGHTS ASSERTION TABLE

Identification and Assertion of Restrictions on the Government's Use, Release, or Disclosure of Technical Data or Computer Software.

The Contractor asserts for itself, or the persons identified below, that the Government's rights to use, release, or disclose the following technical data or computer software should be restricted:

Table 2 - Data Rights Assertion Table

Technical data or computer software to be furnished with restrictions*	**Basis for assertion****	**Asserted rights category*****	**Name of person asserting restrictions******
Catalytic Hot Surface Igniter (CHSI™) (Pat. Pend.)	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Self-Injection Engine Technology (SIETEC License)	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Hybrid Hyper Bar Turbocharger Technology	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Hyper Bar Combustor Design	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Pneumatic Fuel Injection Technology (Pat. Pend.)	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Variable Compression Ratio Valve System (VCRV™) (Pat. Pend.)	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Variable Position Atomizer™ (VPA™) (Pat. Pend)	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
High Pressure Coolant System Design	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Hyper Expansion Crank Mechanism™ (HECM™) (Pat. Pend.)	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Comprex Crankcase Supercharging (Pat. Pend.)	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Compound differential drive coupling enabling automatic on demand boost from mechanical blower versus altitude/load.	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Dual purpose starter motor/generator with governor control to optimize cold start speed (constant angular momentum).	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)

Technical data or computer software to be furnished with restrictions*	Basis for assertion**	Asserted rights category***	Name of person asserting restrictions****
Half keystone low friction ring design with engaged ring gap geometry to ensure uniform radial tension independent of porting.	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
Common desmodromic valve drive system resulting in harmonic motion.	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)
High speed uniflow sleeve valve design / material / manufacturing.	Developed under GSE IRAD	Limited Rights	GSE, Inc (Greg Stevenson)

*For technical data (other than computer software documentation) pertaining to items, components, or processes developed at private expense, identify both the deliverable technical data and each such item, component, or process. For computer software or computer software documentation identify the software or documentation.
**Generally, development at private expense, either exclusively or partially, is the only basis for asserting restrictions. For technical data, other than computer software documentation, development refers to development of the item, component, or process to which the data pertains. The Government's rights in computer software documentation generally may not be restricted. For computer software, development refers to the software. Indicate whether development was accomplished exclusively or partially at private expense. If development was not accomplished at private expense, or for computer software documentation, enter the specific basis for asserting restrictions.
***Enter asserted rights category (e.g., government purpose license rights from a prior contract, rights in SBIR data generated under another contract, limited, restricted, or government purpose rights under this or a prior contract, or specially negotiated licenses).
****Corporation, individual, or other person, as appropriate.
*****Enter "none" when all data or software will be submitted without restrictions.

4. APPENDIX # 1 - AN ALBATROSS AROUND THE US MILITARY'S NECK: THE SINGLE FUEL CONCEPT AND THE FUTURE OF EXPEDITIONARY ENERGY

Paul J. Kern, Walker Mills, Erik Limpaecher, Matt Santoli and Ben Flanagan | 06.29.21

Energy is the lifeblood of our warfighting capabilities.
— *Retired General David Petraeus*

It was 1969, during Capt. Kern's second tour of Vietnam. His fuel logistics hassles were even worse than those he faced his first time in the country when he was a cavalry platoon leader. During that tour, his soldiers had resorted to hanging bags of fuel from trees so that gravity would refuel their M113 armored personnel carriers. If they were in a good spot, they could drive the vehicles into a ditch and rest the fuel bags on the ground. Now Kern was responsible for not just M113s, but an assortment of forty vehicles including M551 Sheridan armored reconnaissance assault vehicles, a borrowed M548 cargo carrier, occasionally an M48 Patton tank, and M118 trailers. Diesel "recipes" were not standardized at the time and varied based on the season and the region. It took a while for the logisticians to get the local mix right. But the real hassle was the M48 and its gasoline. The gas evaporated so quickly in the hot climate and the engines ran so inefficiently that the beast required refueling twice a day. When soldiers unknowingly supplied a bladder full of jet aviation fuel for the affected vehicles it all had to be pumped out after the fact. Little did Kern know that when he arrived at Ft. Stewart years later as a battalion commander, he'd be dealing with an even greater variety of local diesel recipes, gasoline, and jet fuels for his vehicles.

To Gen. Kern and his generation of leaders, the "single fuel concept" (SFC) was a blessing. Historically, the SFC has provided increased interoperability and simplified logistics for the procurement, storage, and transportation of fuel, especially on the battlefield.

The shift toward a single fuel began in the late 1980s, aimed at streamlining the logistics headache of supplying a military that used half a dozen different types of fuel for aircraft and ground vehicles. Under this policy, which has since been further standardized with our NATO allies, the United States military predominantly uses JP-8 fuel to run its ground vehicles and land-based aircraft. JP-8 is commercial jet aviation fuel, with military additives for improved lubrication and inhibition of static, icing, and corrosion. The main advantage of using JP-8 as a common fuel is that unlike diesel and gasoline that can only be used in their respective engines, JP-8 can be used in both turbine-engine aircraft and diesel-powered ground equipment. While JP-8 is not perfectly suited for standard diesel engines, its chemical properties are close enough that the logistical efficiencies outweigh performance drawbacks.

To save costs, in 2012 all the services began switching to F-24 fuel in the United States, excluding Alaska. F-24 is similar to JP-8 but has greater commercial availability—although JP-8 has a lower freezing point, in part why Alaska was exempt from the switch. Overseas, however, the military continues to use JP-8, along with two other types, JP-5 and F-76. JP-5 and JP-8 are both jet fuels that are also used in ground vehicles. JP-5 is preferred for use aboard ships due to its higher flash point temperature. F-76 diesel fuel, which fires the diesel engines, gas turbines, and boilers aboard Navy ships, is formulated to remain stable and usable for years.

By the time Kern was a colonel and the 18th Airborne Corps was about to cross into Iraq during Operation Desert Storm, the SFC had solved the fuel diversity challenges he had faced in Vietnam. This time fuel posed a different problem: the sheer volume required. Before the attack on Jalibah Airfield by the 2nd Brigade, 24th Infantry Division, that he commanded, refueling was only just completed as vehicles were moving into their attack positions.

Single Fuel Dogma and the Supply-Demand Trap

As far as logistics go, the most salient single feature of the warfare in question was its dependence on the internal combustion engine both on land and in the air. For decades

past, everybody had realized that dependence and some sought to reduce it. As of the present, though, instead of being diminished by new technologies it is still increasing.
— Martin van Creveld, Supplying War: Logistics from Wallenstein to Patton

While the SFC was originally meant to standardize the use of liquid fuels, this Cold War–era energy policy has become dogma that threatens the US military's ability to adapt to future conflict and gain tactical and operational benefits. By restricting military users to a single fuel and thereby disincentivizing experimentation with alternatives, it has helped to create the mentality that petroleum fuels are the exclusive energy source in a forward environment. The Department of Defense needs to look past the single fuel concept and fully embrace the recommendations in its 2016 Operational Energy Strategy report to reduce the risks associated with the future operating environment through "innovation" and "diversification" of operational energy.

In 2018, DoD announced formally that alternative fuels were allowed for operational use. While well intentioned, this guidance will do more harm than good since it restricts the department to existing energy systems and processes. The policy limits alternative fuels to drop-in liquid petroleum replacements like synthetic fuels—it does not allow for true alternatives like hydrogen or propane fuels. It requires that alternatives be "compatible with existing equipment and infrastructure" and that producers must "provide significant volumes to support an expeditionary, globally deployed force."

Despite extensive experimentation with alternative fuels at leading federal research labs, SFC dogma is stifling transition into the force at the scale needed to realize tactical and operational benefits. Even though all services have expressed interest and are investing in alternative energy research, the single fuel concept is the most significant barrier to their adoption. Beyond a pervasive bias against incorporating new energy sources into existing energy logistics, any potential implementation of a new fuel suffers from the chicken-and-egg problem where logisticians won't invest in supplying new fuels to platforms that don't exist and acquisitions officers are reluctant to procure new platforms that rely on fuel infrastructure that doesn't yet exist at scale. Without the demand from alternative fuel–powered tactical platforms, there is little incentive for logisticians to create the necessary logistics infrastructure and trained personnel to increase supply. Meanwhile, program managers are not interested in setting requirements for new tactical vehicles that run on a fuel for which there is no supply chain. Both logisticians and program managers accustomed to a single-fuel environment seem unwilling to accept the initial risk of breaking through this supply-demand trap to fund large-scale programs that use new fuels and electric powertrains.

What started as a way to streamline the logistics for US armored units in Europe now threatens to constrain operational energy innovation at a critical time for the US military. The US military is relying on innovative new operating concepts like Multi-Domain Operations and Expeditionary Advanced Base Operations (EABO) to counter aggression by China and Russia, but the concepts for operational energy are stuck in the Cold War. Distributed operations, seen as a critical piece to all of the services' emerging operating concepts, will strain logistics networks in new ways, especially with regard to fuel and operational energy.

Leaders inside and outside the Pentagon, however, fear that the US military will be unable to operationalize new warfighting concepts because outdated logistics will be the limiting factor. Marine leaders have become increasingly preoccupied with the challenge of distributed and contested logistics in the Pacific. Wargaming in the service has shown that sustainment, particularly fuel sustainment, is a leading operational constraint. The commandant did not mince words with his assessment in 2020:

I am not confident that we have identified the additional structure required to provide the tactical maneuver and logistical sustainment needed to execute DMO [Distributed Maritime Operations], LOCE [Littoral Operations in a contested Environment] and EABO in contested littoral environments against our pacing threat.

While the House Armed Services Committee's Future of Defense Task Force report identified emerging operational concepts as one of the primary ways the Pentagon can provide the US military with a "decisive advantage" in future conflicts, it cautioned that "they are not yet fully viable." The 2016 Department of Defense Operational Energy Strategy warned that "these logistically intensive future concepts may not be supportable." Even adversaries have messaged the US military that maritime logistics will be contested. A RAND Corporation report found that both China and Russia could launch an "interdiction campaign" in a conflict to restrict the flow of battlefield necessities, including fuel, to US forces, further complicating logistics.

The Promise of Alternatives

Despite multiple attempts to de-escalate, the United States was forced to engage militarily in 2030 to protect its allies in the western Pacific. Capt. Smith had been recently assigned to the Marine Littoral Regiment in III Marine Expeditionary Force. His experimental infantry company was tasked with establishing an expeditionary advanced base. One platoon ran a hydrogen forward arming and refueling point (H-FARP) system that could rapidly refuel their array of hydrogen-powered platforms: Stalker and Blackjack UAVs, Reckless utility terrain vehicles (UTVs), and stratellites—small stratospheric balloons that temporarily *provide satellite-like capabilities. The long-endurance hydrogen-powered UAV allowed Capt. Smith's company to maintain persistent UAV coverage around the clock, scanning the adjacent seas for enemy ships. Without the three-times-longer flight endurance enabled by the hydrogen power train, this mission would have been impossible. Another platoon hitched a radar and antiship missile launcher to hydrogen-powered UTVs and drove along the coastline, scanning the skies for enemy aircraft and, if necessary, providing fires. Thanks to the vehicle's hydrogen fuel cells, which ran efficiently even when idling, these Marines were able to keep their radar and communications gear powered without emitting any detectable thermal or audible signature. When the adversary jammed GPS and communications, Smith's platoons quickly reestablished secure comms and navigation with the launch of two hydrogen-fueled stratellites that they could deploy themselves at 0.002 percent of the cost of a new satellite and would loiter for days. Meanwhile adjacent units not equipped with alternate sources of energy struggled after enemy missile strikes destroyed their prepositioned fuel stores and adversary submarines and land-based missiles prevented the Navy and Maritime Sealift Command from bringing in bulk fuel.*

DoD has been studying, prototyping, and experimenting with several alternatives to petroleum for decades but these have not been deployed in quantity. This essay focuses on the most promising energy sources for tactical power. Other alternatives like solar, wind, and geothermal have been integrated into installations infrastructure but their low efficiency makes them poor options for use during operations.

Ammonia: A liquid when compressed, ammonia is produced from hydrogen and nitrogen. Even though it is caustic and hazardous in concentrated form, it sees wide industrial use. In the 1960s the Army developed the "Energy Depot Concept," which would have used a small nuclear reactor to produce hydrogen and nitrogen as feedstock for ammonia. Commercial shipping companies in Japan and Europe are working to use ammonia as the fuel for cargo ships to eliminate carbon emissions.

Synthetic Fuels, Alcohol Fuels, and Biofuels: All US Air Force aircraft have now been certified to fly using a 50 percent synthetic fuel blend made though the Fischer-Tropsch process, of which ten million gallons are expected to be produced daily by 2030. More than 98 percent of the gasoline sold in the United States contains ethanol, the most common biofuel, to increase octane and reduce emissions. Ethanol and other alcohol fuels can also be fed through fuel cells without needing oxygen, which makes them leading candidates for use in unmanned undersea vessels. In 2013 the secretary of the Navy announced that "the Great Green Fleet will signal to the world America's continued naval supremacy, unleashed from the tether of foreign oil" by operating on 50 percent biofuel and implementing fuel efficiency measures. The Navy demonstrated the effectiveness of this approach in 2015 when the USS *Makin Island* was able to stay at sea over a month longer than it previously had by using biofuels.

Mobile Nuclear Power: By packaging reactors into a standard shipping container and designing them to avoid catastrophic meltdowns despite physical damage, nuclear power has the potential to address DoD's tactical power needs. In late 2020 the Energy and Defense Departments issued contracts for prototype small, modular, and mobile nuclear reactors. Companies such as HolosGen and X-energy are currently developing and marketing miniature, mobile nuclear energy platforms for commercial and government use. Nuclear fuel innovations such as tri-structural isotropic particle fuel promise more robust and inherently safer reactor operation, by encapsulating small particles of nuclear fuel in individual safety packages. However, independent reports have criticized the idea as being too expensive and too risky.

Hydrogen: Hydrogen holds significant potential for DoD, since it can be produced within theater, both regionally and locally from numerous energy sources. Traditional production techniques use coal, natural gas, or burned waste. Electrolyzers, which consume electric power and water, are the leading method for producing zero-emissions "green" hydrogen. US allies across the globe are making significant investments in hydrogen, with the Japanese building a "hydrogen society," the French investing €7 billion to build 6.5 gigawatts of electrolyzer capacity, the Germans exploring the possibility of using gas pipelines to carry 100 percent hydrogen rather than Russian natural gas, and the Australians aiming to become a "hydrogen powerhouse." Multiple organizations are developing novel ways to produce hydrogen from recycled aluminum.

The military has been building prototypes to demonstrate the benefits of hydrogen power for nearly two decades. The Naval Research Lab and Army Ground Vehicle Systems Center have successfully developed several hydrogen-fueled platforms, including record-shattering UAVs. Vendors for both the US Army and European militaries are developing packable fuel cells to charge soldiers' lithium-ion batteries. DoD has successfully produced synthetic petroleum fuel from hydrogen and carbon dioxide extracted from seawater, and could produce synthetic petroleum from the exhaust of diesel generators at home or abroad.

Enable our Future Commanders

During his military career, Gen. Kern, his soldiers, and the logisticians who supported them benefited from the standardization and simplified logistics offered by the single fuel concept. In the intervening forty years, the commercial sector has revolutionized power and energy technologies. Commercially available products that use nonpetroleum fuels provide capabilities that internal combustion engines simply cannot. Nonpetroleum fuels also hold the potential for regional and local production, which would finally sever, or at least shorten, what retired General James Mattis once described as DoD's "tether of fuel."

It is time to update the single fuel concept to encourage the adoption of platforms powered by nonpetroleum fuels and build the required logistical infrastructure. Just as fuel policy enabled Gen. Kern and his generation to win during Operation Desert Storm, a modernized fuel policy will enable future military leaders, such as the younger officers on the byline, to win our nation's future conflicts.

General (ret) Paul Kern has thirty-eight years of service in the US Army including time as commanding general of the Army Materiel Command, commander of the 4th Infantry Division, and commander of 2nd Brigade, 24th Infantry Division during the 1991 Persian Gulf War.

Captain Walker Mills is a Marine infantry officer currently serving as an instructor at the Colombian Naval Academy in Cartagena, Colombia. He is also the Military Fellow with Young Professionals in Foreign Policy and a fellow at the Brute Krulak Center for Innovation and Future War.

Captain Matthew Santoli is a Marine artillery officer and a recent graduate of the Harvard Kennedy School's Master in Public Policy (MPP) program.

First Lieutenant Benjamin Flanagan is an Air Force pilot trainee and a recent graduate of the Harvard Kennedy School's MPP program.

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The views expressed are those of the author(s) and do not reflect the official position of the United States Military Academy, Department of the Army, or Department of Defense.

Image credit: Sgt. Gregory T. Summers, US Army

5. APPENDIX # 2 - TECHNICAL READINESS LEVEL DEFINITIONS UTILIZED

Table 3 - Technical Readiness Level Table

Technical Readiness Level (TRL)	Description	Example
1	Basic principles observed	• Scientific observations made and reported. • Examples could include paper-based studies of a technology's basic properties.
2	Technology concept formulated	• Envisioned applications are speculative at this stage. • Examples are often limited to analytical studies.
3	Experimental proof of concept	• Effective research and development initiated. • Examples include studies and laboratory measurements to validate analytical predictions.
4	Technology validated in lab	• Technology validated through designed investigation. • Examples might include analysis of the technology parameter operating range. The results provide evidence that envisioned application performance requirements might be attainable.
5	Technology validated in relevant environment	• Reliability of technology significantly increases. • Examples could involve validation of a semi-integrated system/model of technological and supporting elements in a simulated environment.
6	Technology demonstrated in relevant environment	• Prototype system verified. • Examples might include a prototype system/model being produced and demonstrated in a simulated environment.
7	System model or prototype demonstration in operational environment	• A major step increase in technological maturity. • Examples could include a prototype model/system being verified in an operational environment.
8	System complete and qualified	• System / model produced and qualified. • An example might include the knowledge generated from TRL 7 being used to manufacture an actual system / model, which is subsequently qualified in an operational environment. In most cases, this TRL represents the end of development.
9	Actual system proven in operational environment	• System / model proven and ready for full commercial deployment. • An example includes the actual system/model being successfully deployed for multiple missions by end users.

6. APPENDIX # 3 – HYPER-BAR TURBOCHARGING EXPLAINED

As illustrated in Figure 43 below, the "Hyper-Bar Turbo" takes the oxygen rich exhaust from a diesel or heavy fuel engine and injects additional fuel into the waste exhaust gas stream. It then ignites said waste stream to turn a turbine at a higher energy rate that in turn drives a compressor to a much higher pressure than a standard turbocharger. It should be noted for Hyper-Bar Turbocharging to be effective; the host engine must be a low compression engine to accept the significant (double) the weight of air for compression and peak power output.

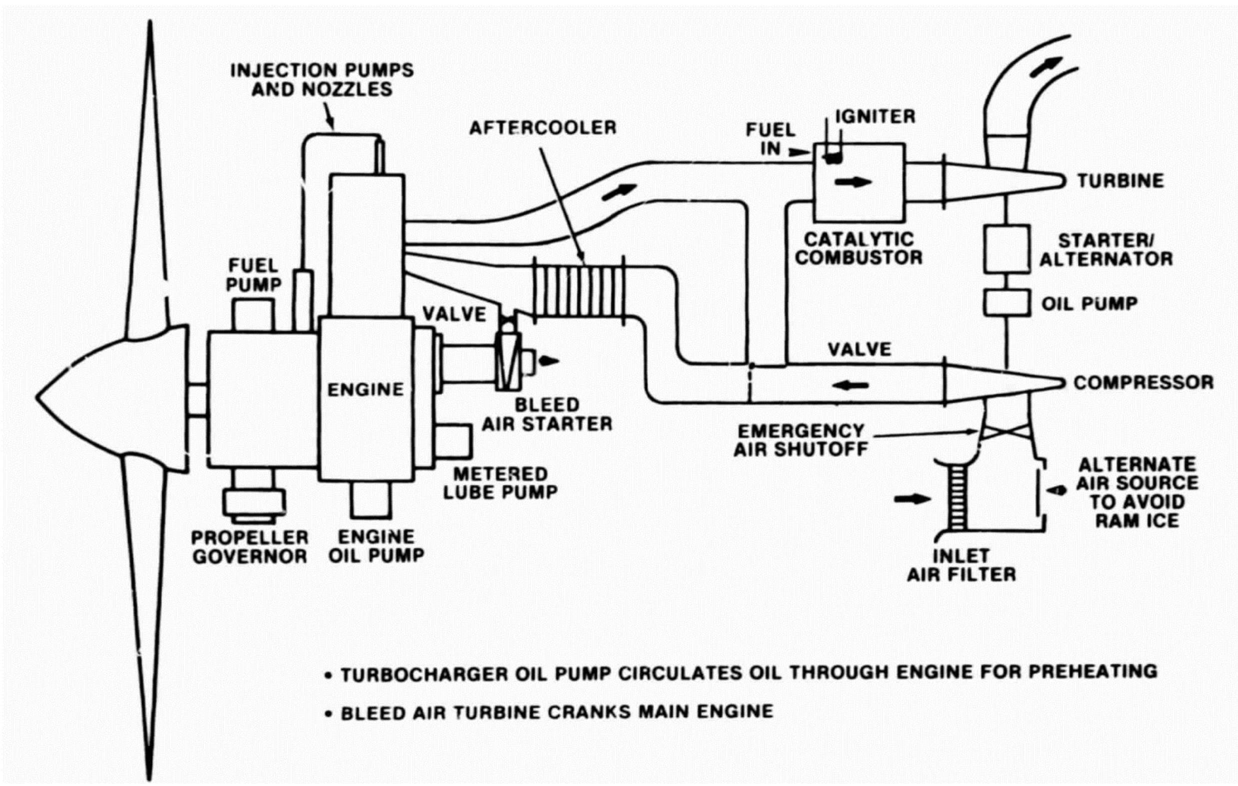

Figure 2- Hyper-Bar Turbo Illustrated on 2-Stroke Engine with Independent Turbo Loop

7. APPENDIX # 4 – SLEEVE VALVE[3] AND ASPIN VALVE[4] ENGINES EXPLAINED

As stated in the book, "Some Unusual Engines"[7],

> *There have been many extremely unusual engines conceived, designed, and occasionally built, by would-be iconoclasts. Precious few of them have ever enjoyed any kind of commercial success, even those which were proved to work well. The reason is not far to seek: if there by anybody more conservative than an engine manufacturer, it is his customer. Traditions exist to be followed, and it is only where there are not traditions, and where it is accepted that an engine has some particular duty to do but is otherwise likely to be covered up and ignored by everybody except the minions delegated to look after it, that unconventional engines have any chance to prosper. Such applications are rare and most of them are military, although marine engineers at various levels from the outboard motor to the giant ocean-going diesel seem to be surprisingly open-minded.*

With that statement in mind, it is time that the aerospace industry started becoming more open-minded especially if they want to see a major engine technology breakthrough. The last major internal combustion engine breakthrough was in the post-war era of the 1950's. In the past, there have been various technologies utilized very successfully and in fact have had longer mean time to failures than conventional engine technology.

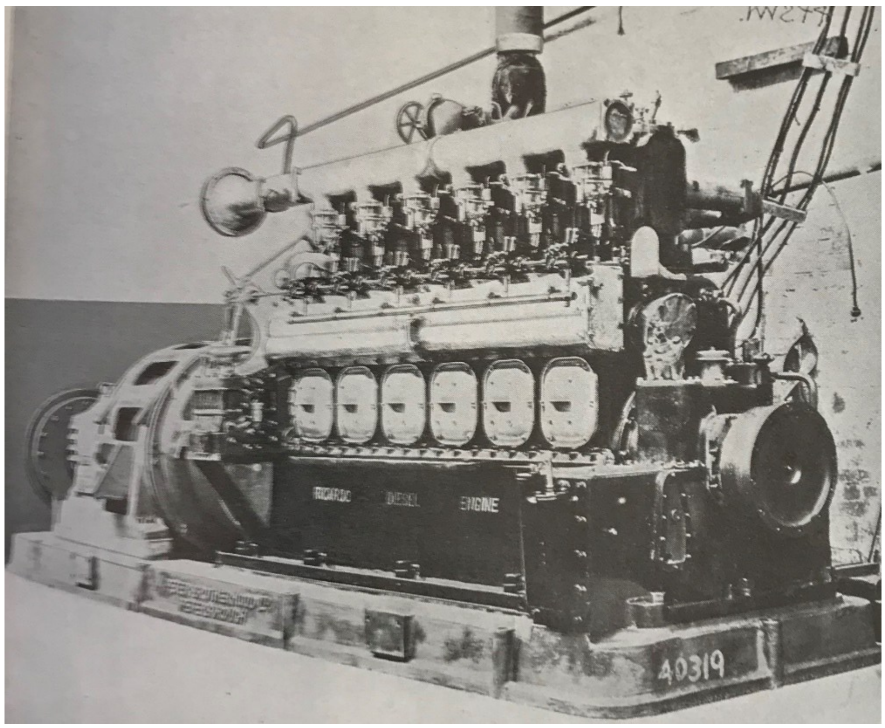

Figure 3 - Brotherhood-Ricardo six-cylinder sleeve valve / generator set

A couple of the technologies that have been ignored has been the "Sleeve Valve" engines who have huge mean to failure rates (a Brotherhood/Ricardo Stationary Generator running a sleeve valve engine achieved over 60,000 hours before failure {See Figure 50}), and the Aspin valve engines. Both technologies do not have poppet valves blocking the ports therefore, the air or exhaust flows through freely. By doing this, incoming air or exhaust can flow through the ports unobstructed and at a faster rate than you will find in poppet valve engines. The sleeve valve engine has a sleeve that is inside the cylinder and the piston is inside the sleeve. Typically, the sleeve is "floating" on a thin film of oil that helps to prevent wear on the cylinder and will commonly have 3 intake and 2 exhaust ports. In addition, the piston is also floating on a thin film of oil plus since the sleeve is not only in motion up and down; but also rotating from side

[3] (Sir Harry R. Ricardo, 1953 (Reprinted 1962)) Page 345
[4] (Setright, 1975 (1979)) Pgs 47-52

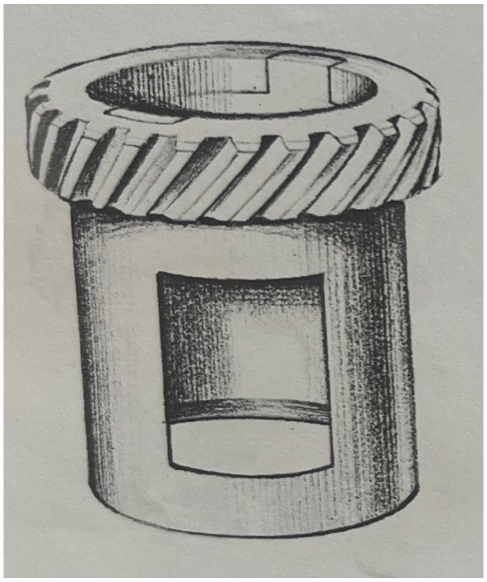

Figure 4 - Version 2 of the Aspin valve

to side, you don't get the wear spots that you would normally see on an internal combustion engine. Similarly, the Aspin valve engines have a gear driven valve that rotates within the engine providing a similar non-obstructed opening like a sleeve valve engine, they also allow unrestricted flow through the Aspin valves 2 ports. Conversely, poppet valve engines require large valves that restrict the port openings and cannot accelerate or decelerate fast enough to get air in and out of the cylinders in an efficient manner. Whereas both the Aspin valve and the sleeve valve engines provide maximum flow of gases in and out of the cylinder at exactly the precise moment it is needed without obstructing the port opening and, in many instances, due to the highly effective scavenging nature of both engines some of the unburnt gases return to the cylinders to mix with the incoming fresh air. In addition, since both engine types have low in cylinder compression ratios that allow large quantities of air to flow in and get on the lean side of stochiometric with near 18:1 as a final internal compression ratio.

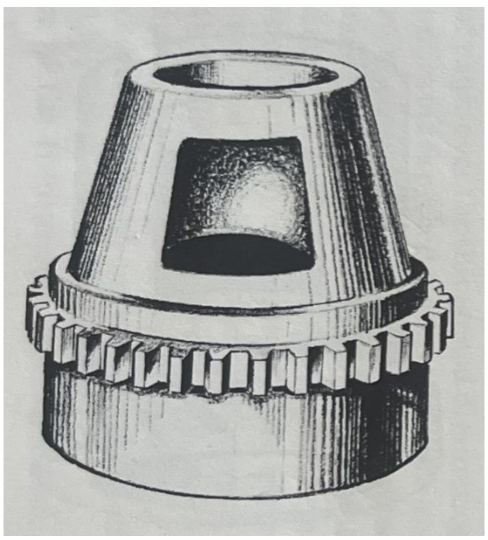

Figure 5 - Version 3 of the Aspin valve

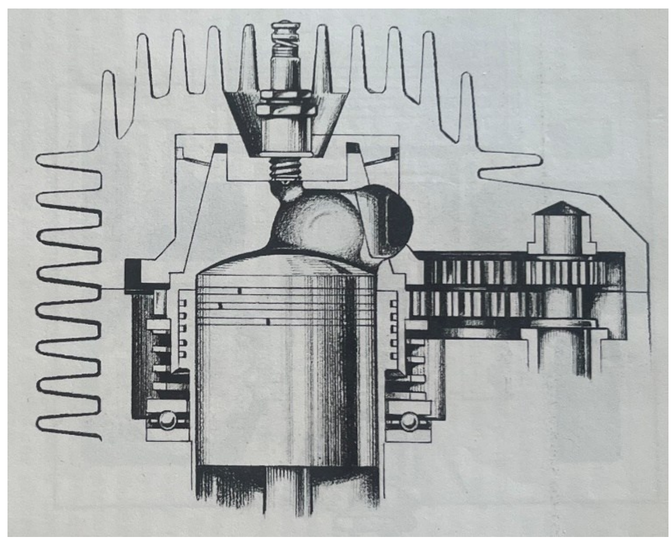

Figure 6 - Aspin valve engine utilizing ver. 3 Aspin valve

Some of the other great benefits of both engine types are:

- Lower exhaust temperatures.
- Lower emission noise.
- Lower NOx emissions due to cooler operating temperatures.
- Immunity to knock, detonation or pre-ignition as the fuel is injected into the cylinder at almost the same time as it is supposed to be ignited.
- Typically, both engine types have fewer parts than most poppet valve engines.
- Since they run at lower temperatures and lower compression, the engines can be made of lighter materials such as aluminum or titanium.

Furthermore, both engines are insensitive to fuel, can be run at high compression ratios on low-grade fuel, it is irrelevant if the fuel contains lead or not and are indifferent to the type of fuel it is. As an example of this, Frank Aspin (the inventor of the Aspin valve) in the post-war era of World War II built a 4.5-liter truck engine as an experiment that he ran on creosote with a specific fuel consumption of 0.4 lb./hp-hr. The efficiency of both types of engines are very high and can be setup as either a 2-cycle or 4-cycle engines.

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