PENNSTATE ARL

Applied Research Laboratory
The Pennsylvania State University

Powered by Naval Research

# A Next-Generation AUV Energy System Based on Al-Seawater Combustion


BY:

Timothy F. Miller, Jeremy L. Walter, Daniel H. Kiely



PRESENTED AT:

AUV 2002: A Workshop on AUV Energy Systems

21 June 2002

PENNSTATE ARL

Applied Research Laboratory
The Pennsylvania State University


# Research Supported by:

- Office of Naval Research (ONR)
- DARPA

4225 W-hr/kg

11,400 W-hr/L

| Fuel | Oxidizer | Energy Source | Specific Energy MJ/kg (HP-Hr/LB) | | Energy Density MJ/m$^3$ ( HP-HR/FT$^3$ | |
|---|---|---|---|---|---|---|
| **Al** | **$H_2O$** | **Open** | **15.2** | **(2.56)** | **41143** | **(434)** |
| Al | $LiClO_4$ | Closed | 12.5 | (2.12) | 31758 | (335) |
| Mg | $F_2$ | Closed | 18.1 | (3.06) | 28724 | (303) |
| Li | $F_2$ | Closed | 23.7 | (4.00) | 23984 | (253) |
| Mg | $ClF_3$ | Closed | 13.1 | (2.22) | 23510 | (248) |
| **Al/Li** | **$LiClO_4$** | **Closed** | **15.9** | **(2.68)** | **21804** | **(230)** |
| Mg | $O_2$ | Closed | 14.9 | (2.52) | 21520 | (227) |
| Li | $ClF_3$ | Closed | 17.4 | (2.94) | 20382 | (215) |
| Li | $LiClO_4$ | Closed | 16.9 | (2.86) | 18486 | (195) |
| Al | $O_2$ | Closed | 16.5 | (2.78) | 18107 | (191) |
| Li | $FClO_3$ | Closed | 17.7 | (2.99) | 15737 | (166) |
| Mg | $SF_6$ | Closed | 10.3 | (1.74) | 15452 | (163) |
| B | $O_2$ | Closed | 17.4 | (2.94) | 14694 | (155) |
| **Li** | **$SF_6$** | **Closed** | **14.7** | **(2.48)** | **14030** | **(148)** |
| Li | $O_2$ | Closed | 22.9 | (3.87) | 13651 | (144) |
| **JP-5** | **$LiClO_4$** | **Semi-Closed** | **6.8** | **(1.15)** | **13082** | **(138)** |
| Li | $CF_4$ | Closed | 12.7 | (2.15) | 11850 | (125) |
| Li | $Cl_2$ | Closed | 9.6 | (1.63) | 11471 | (121) |
| $B_2H_6$ | $O_2$ | Semi-Closed | 18.0 | (3.05) | 10144 | (107) |
| Otto II | | Open | 2.5 | (0.43) | 3223 | (34) |

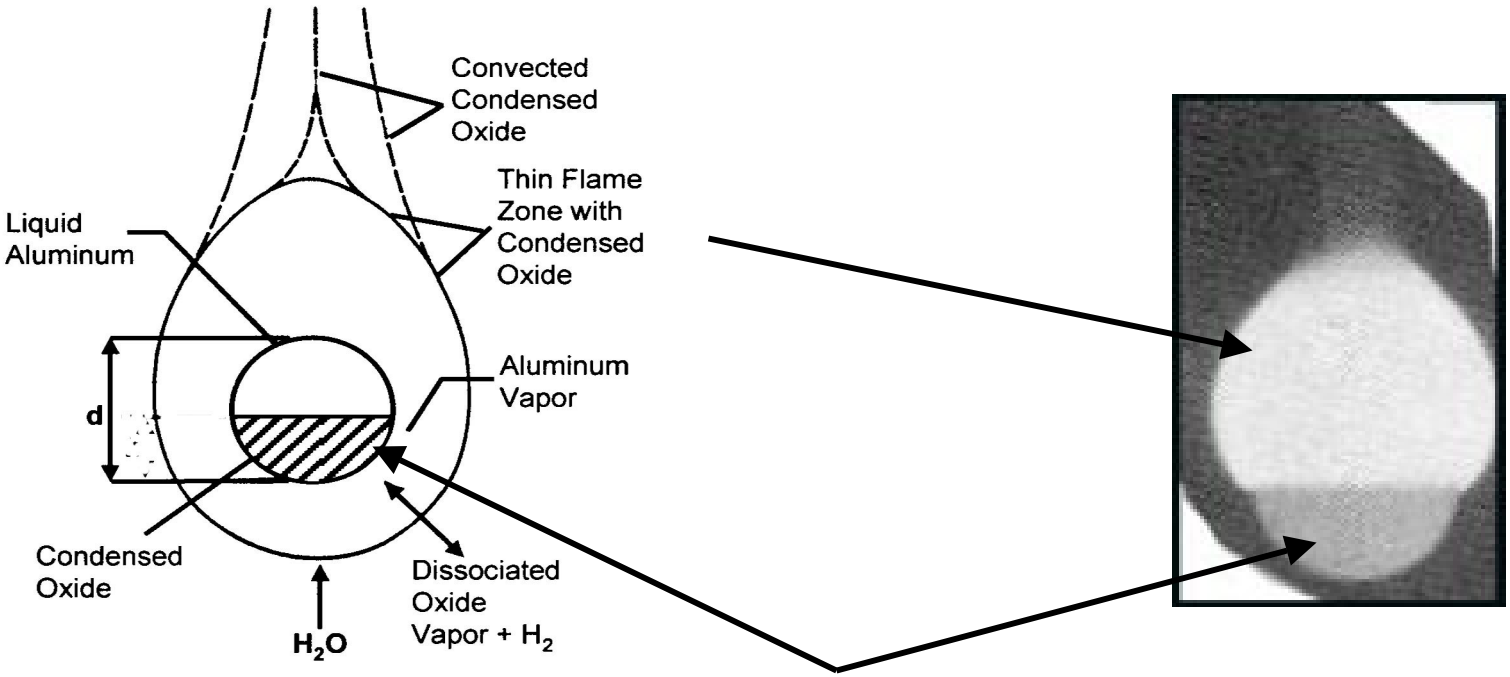
$O_2$ = 680 atm GOX

1 MJ/kg = 278 W-hr/kg

1 MJ/m$^3$ = 0.28 W-hr/L

# Physical Understanding

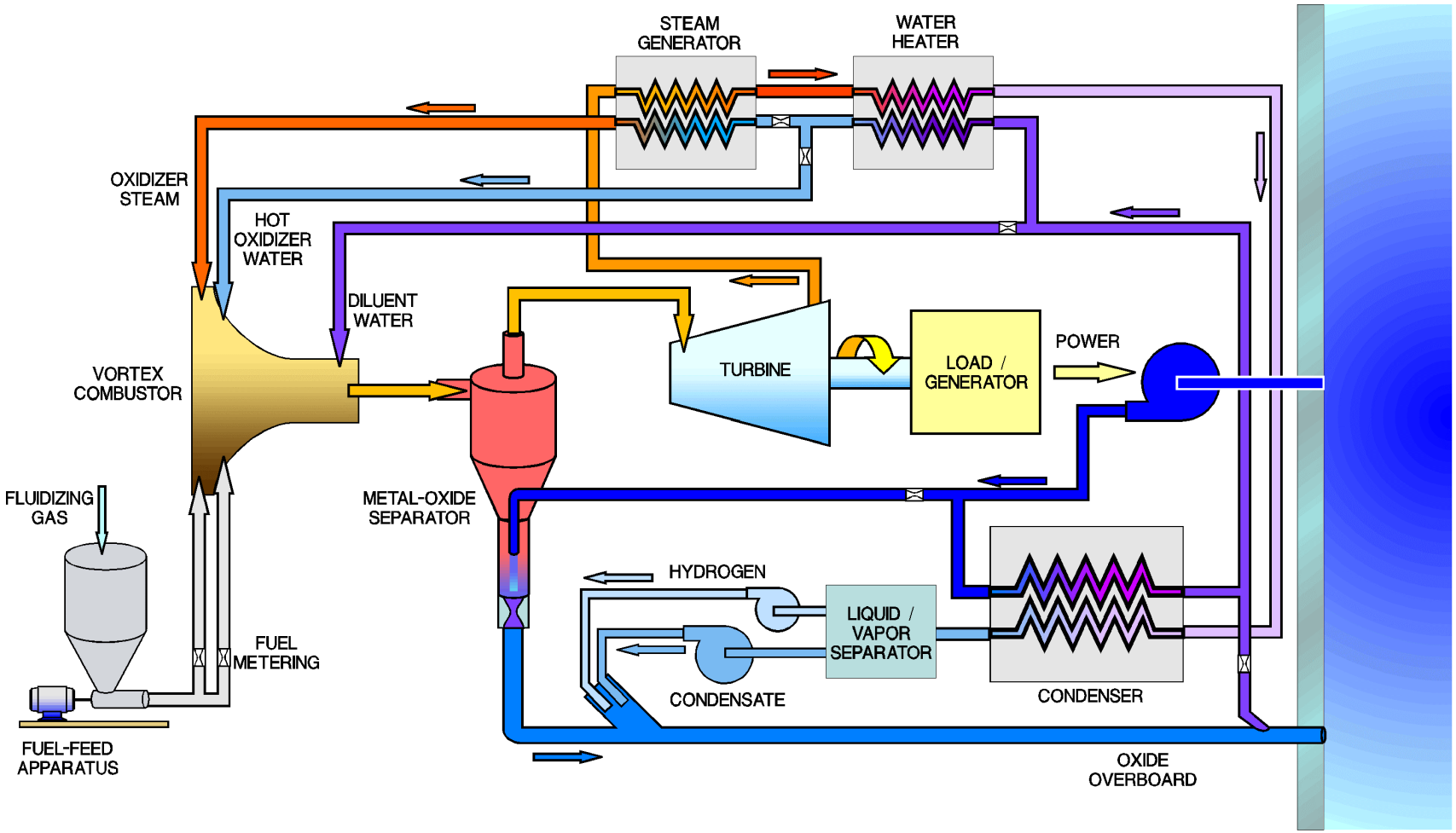
- Al evaporates from droplet surface
- Oxidizer diffuses through boundary layer of gaseous products to react with Al vapor



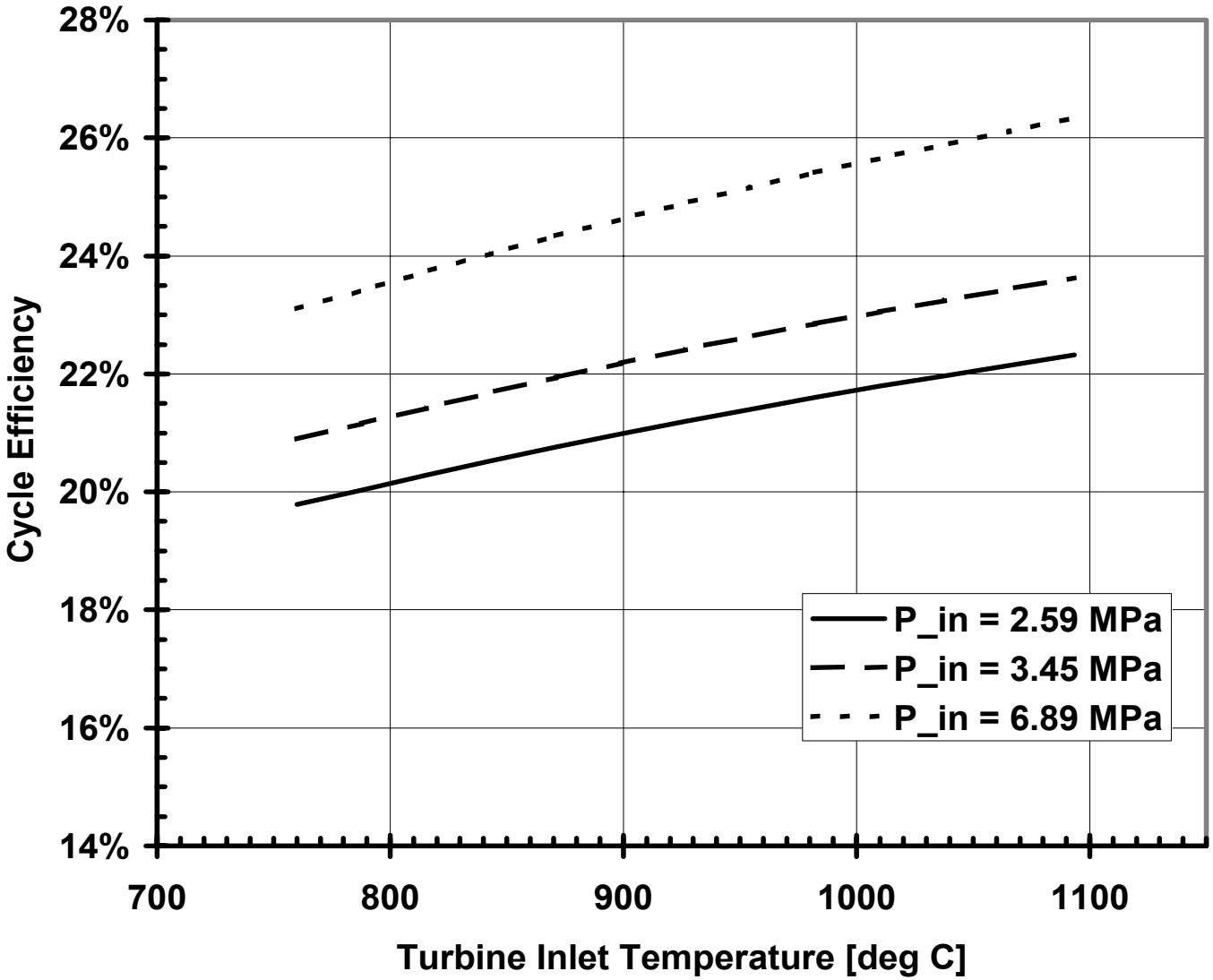

- 10-20 % of oxide condenses on particle ( the amount can be predicted by 1st law energy balance )
- Final oxide particle ~ 40 % initial Al diameter

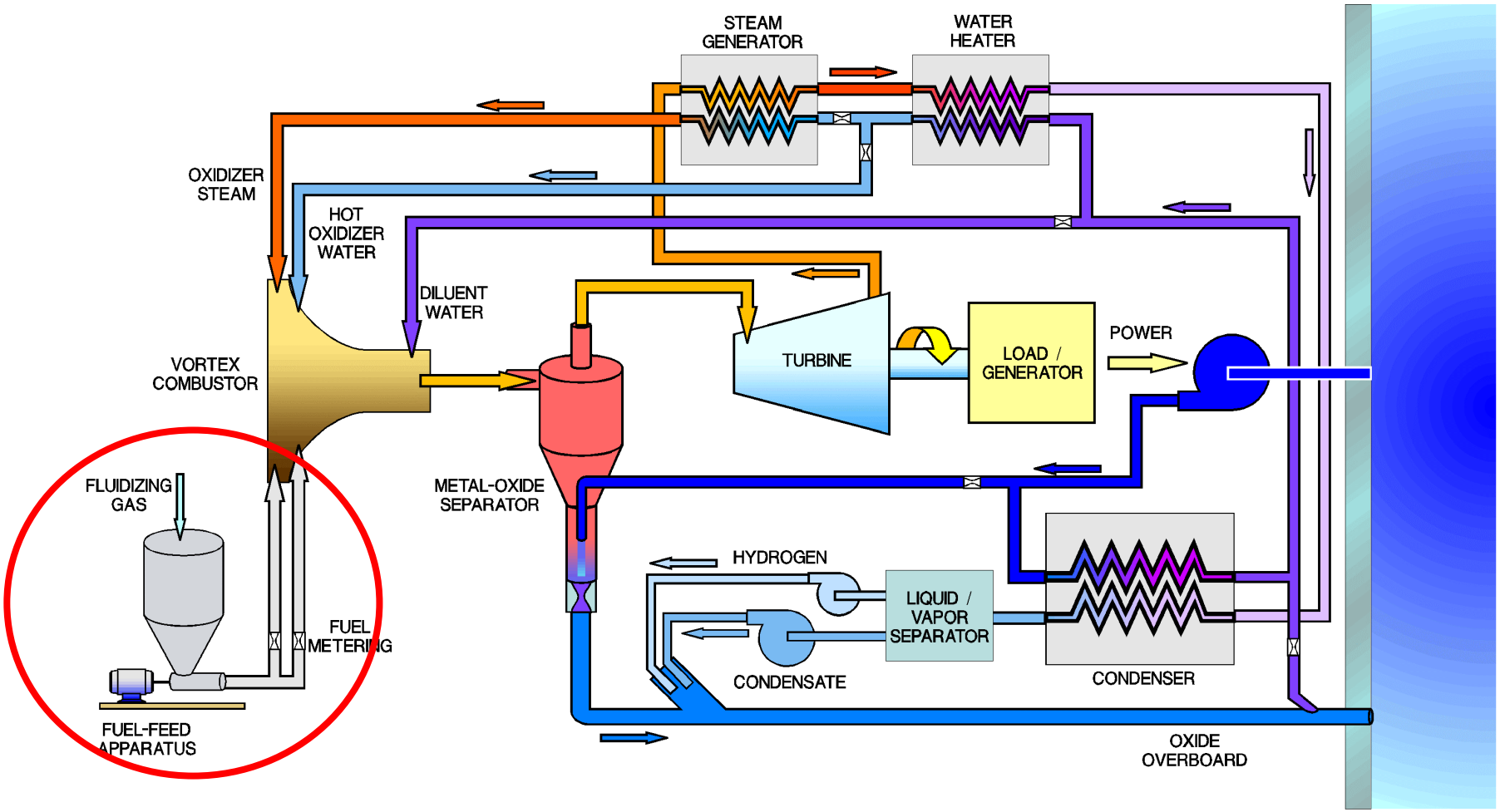
# VORTEX COMBUSTOR POWER SYSTEM

## SYSTEM SCHEMATIC

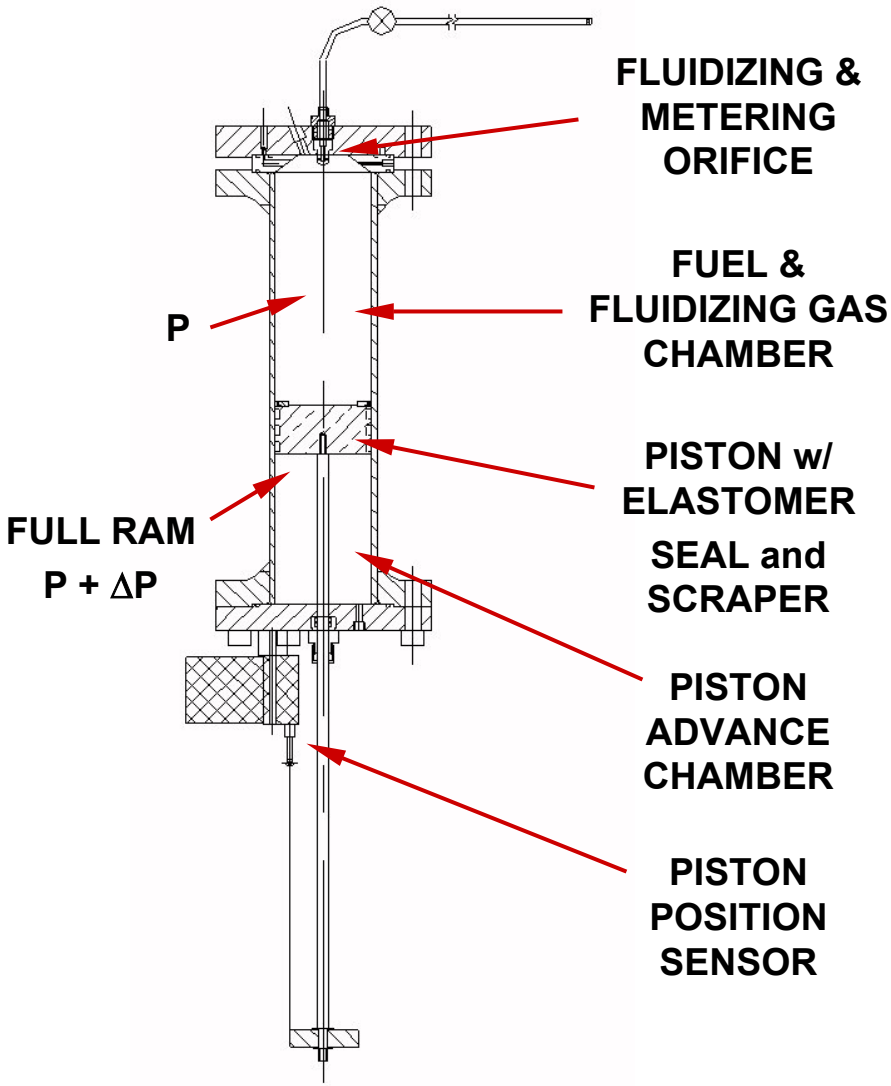


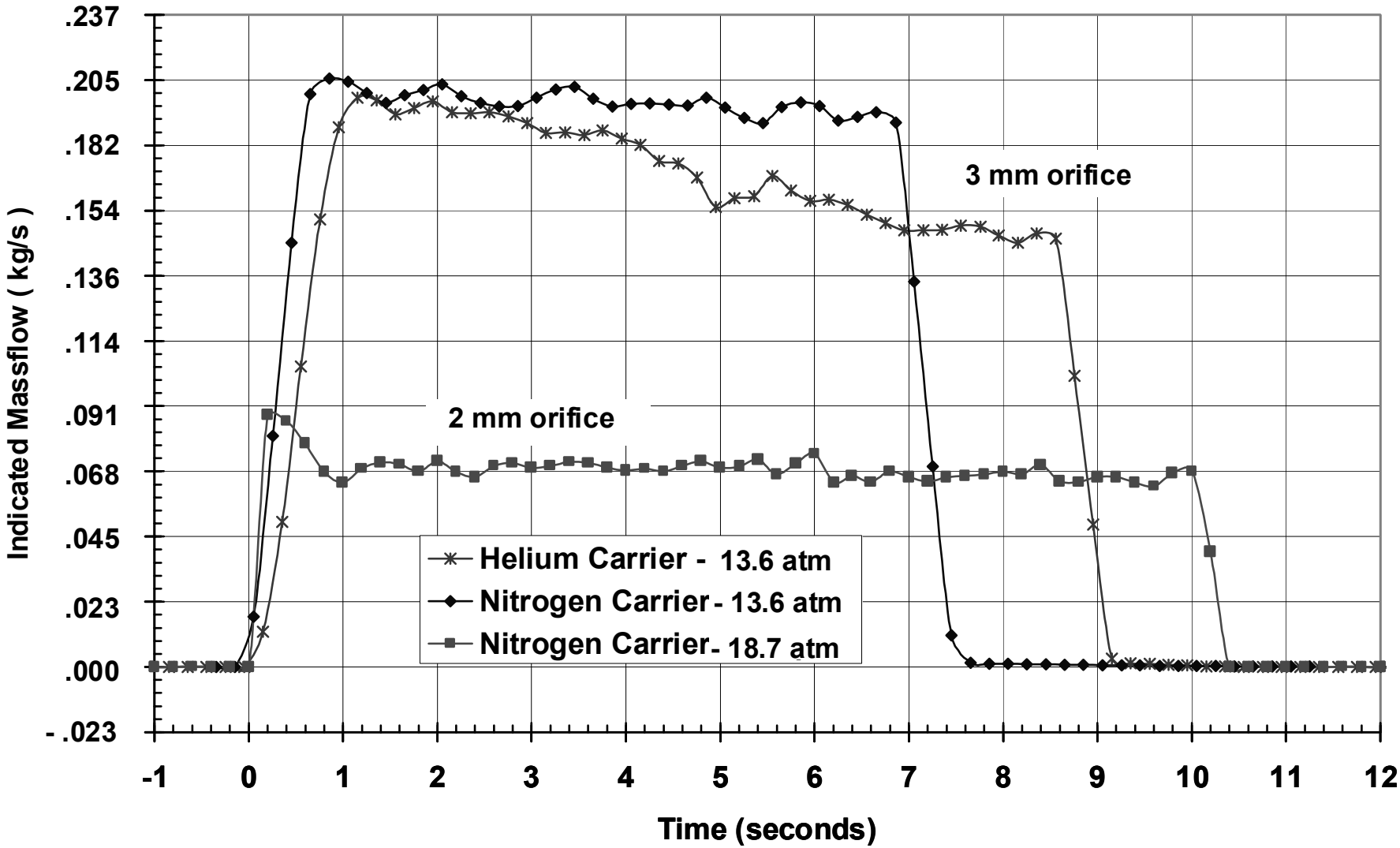
Predicted cycle efficiencies for the proposed Al-seawater AUV energy system at different turbine inlet temperatures and pressures

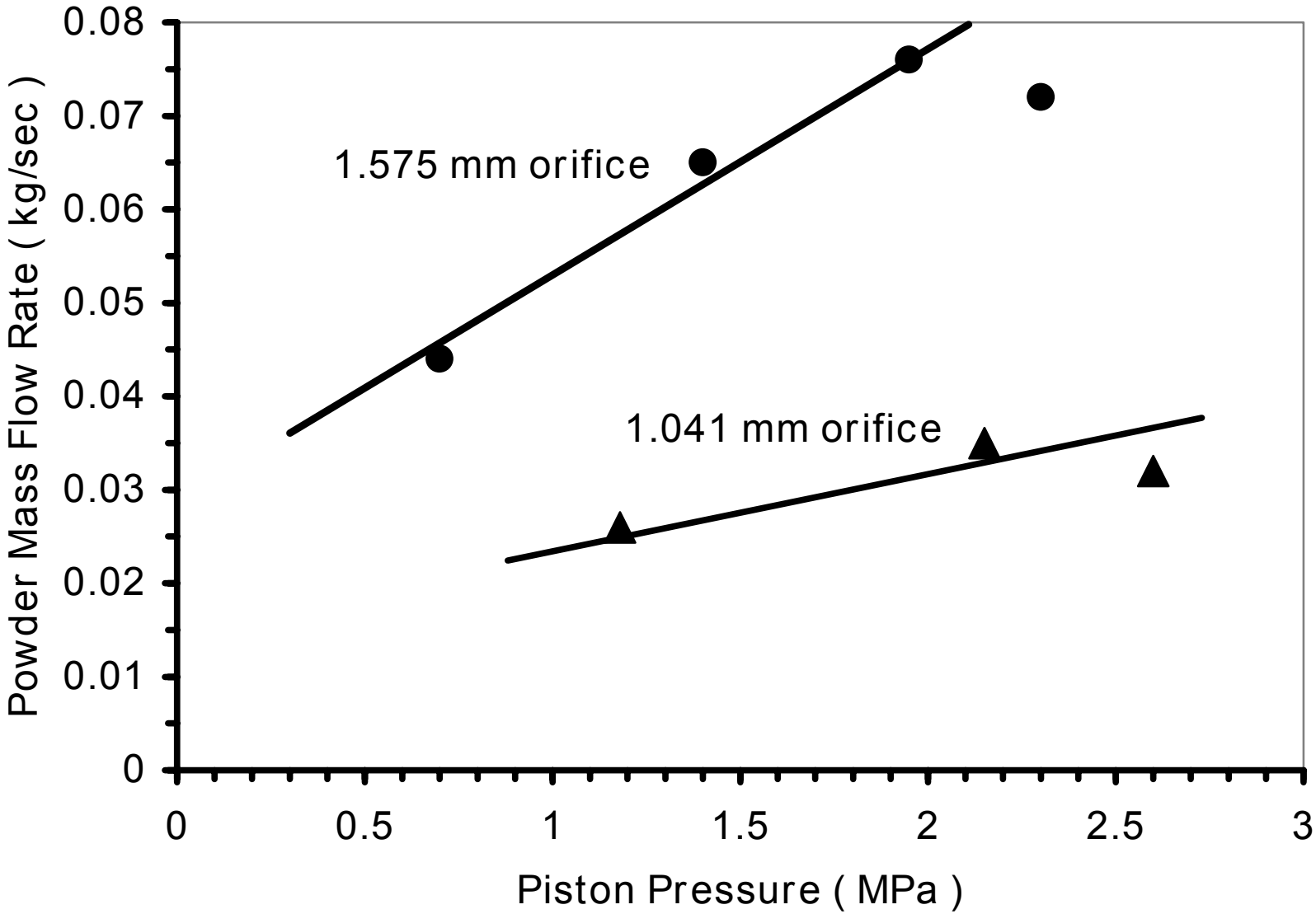


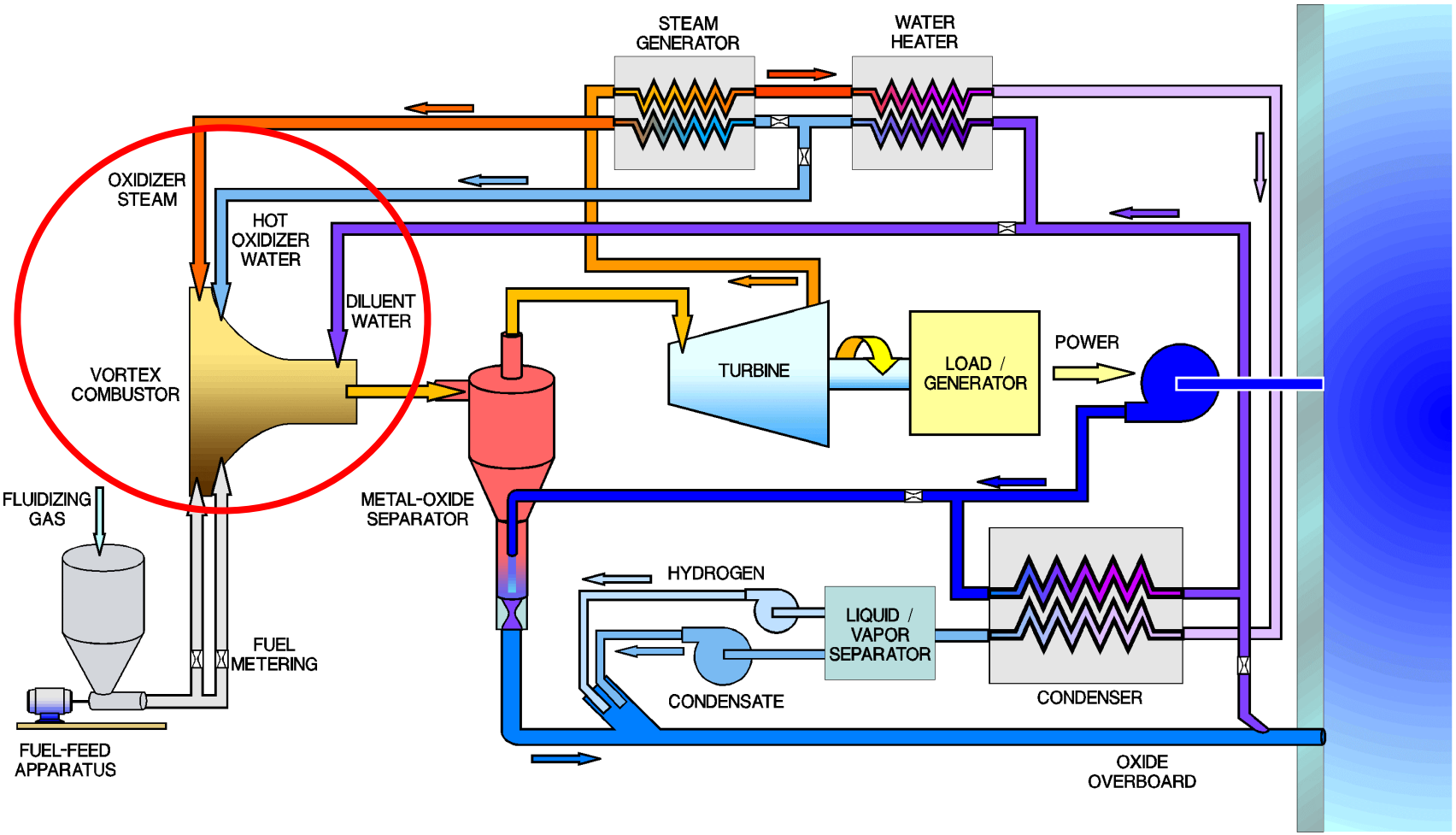

STEAM GENERATOR
WATER HEATER
OXIDIZER STEAM
HOT OXIDIZER WATER
DILUENT WATER
VORTEX COMBUSTOR
TURBINE
LOAD / GENERATOR
POWER
FLUIDIZING GAS
METAL-OXIDE SEPARATOR
HYDROGEN
LIQUID / VAPOR SEPARATOR
FUEL METERING
CONDENSATE
CONDENSER
FUEL-FEED APPARATUS
OXIDE OVERBOARD

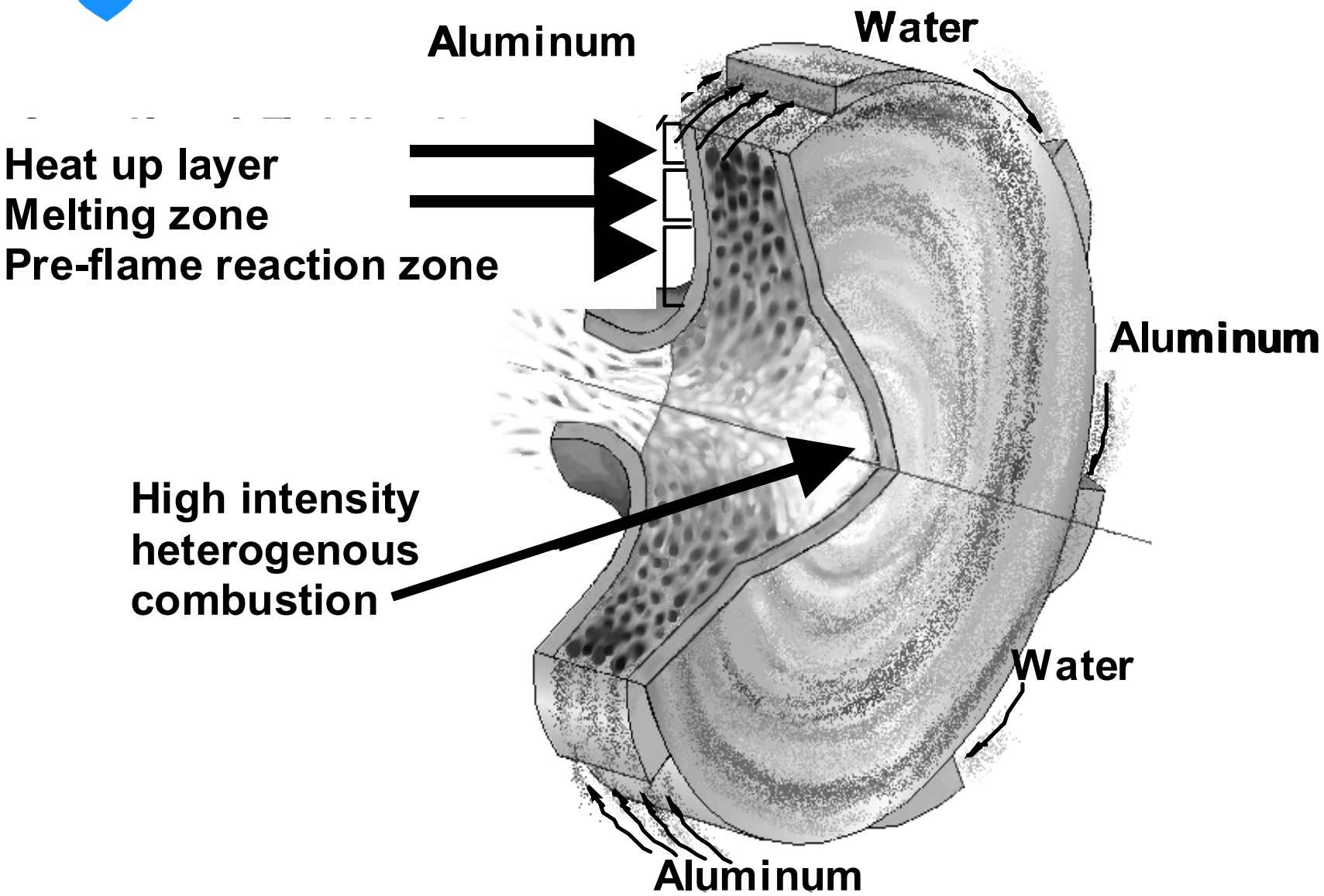
# DENSE-PHASE FLUIDIZER FUEL FEED SYSTEM



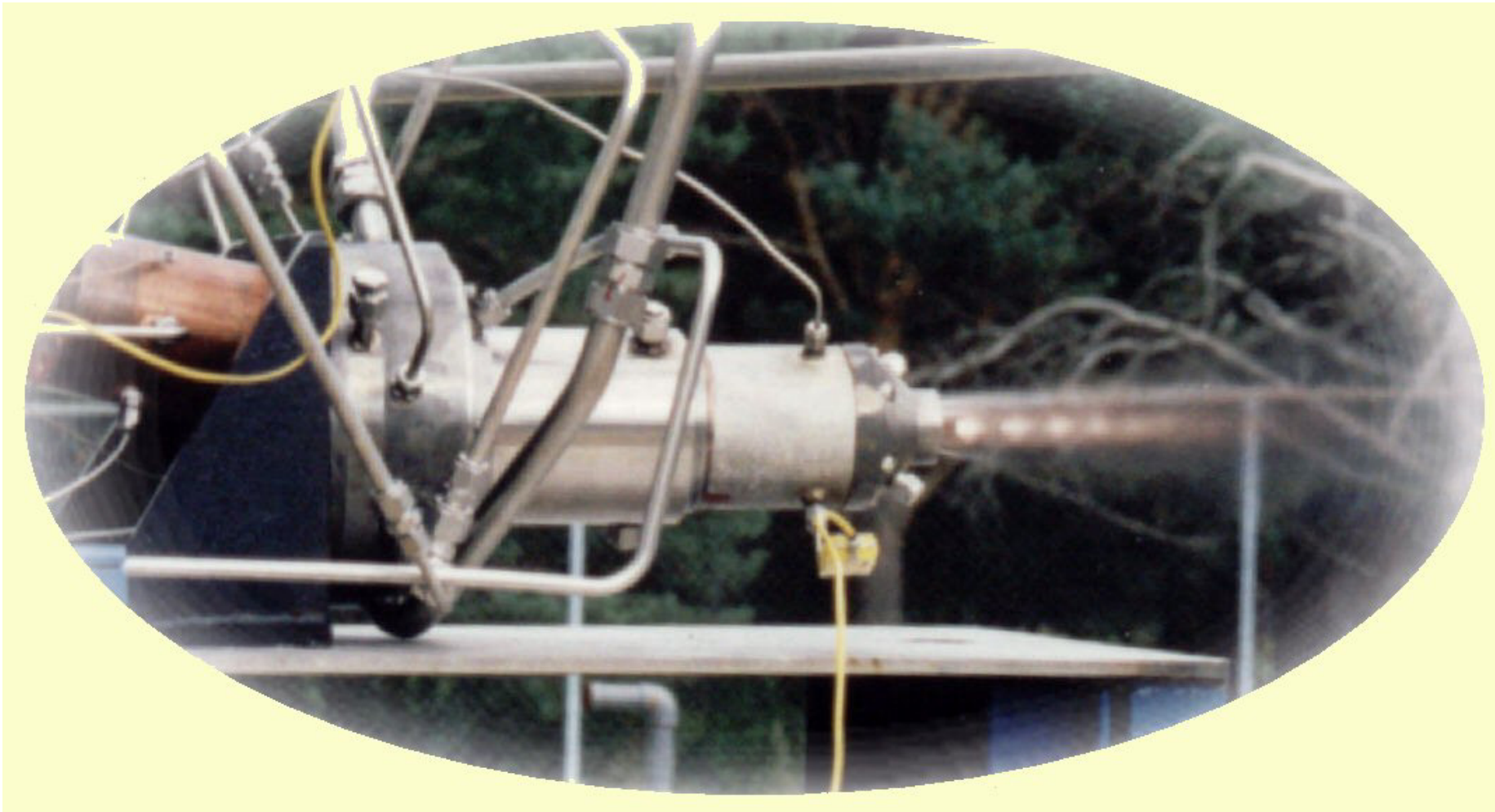


.237
.205
.182
.154
.136
.114
.091
.068
.045
.023
.000
- .023
Indicated Massflow ( kg/s )
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (seconds)
3 mm orifice
2 mm orifice
Helium Carrier - 13.6 atm
Nitrogen Carrier - 13.6 atm
Nitrogen Carrier - 18.7 atm


0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Powder Mass Flow Rate ( kg/sec )
1.575 mm orifice
1.041 mm orifice
0
0.5
1
1.5
2
2.5
3
Piston Pressure ( MPa )


STEAM GENERATOR
WATER HEATER
OXIDIZER STEAM
HOT OXIDIZER WATER
DILUENT WATER
VORTEX COMBUSTOR
TURBINE
LOAD / GENERATOR
POWER
FLUIDIZING GAS
METAL-OXIDE SEPARATOR
HYDROGEN
LIQUID / VAPOR SEPARATOR
CONDENSATE
CONDENSER
FUEL METERING
FUEL-FEED APPARATUS
OXIDE OVERBOARD

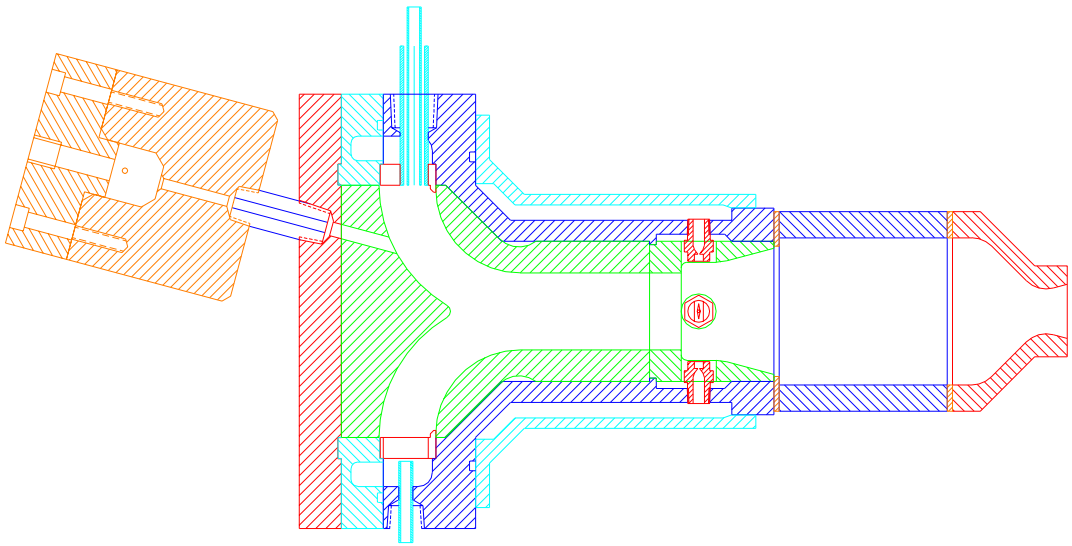

Aluminum
Water
Heat up layer
Melting zone
Pre-flame reaction zone
Aluminum
High intensity
heterogenous
combustion
Water
Aluminum

# Aluminum Vortex Combustor

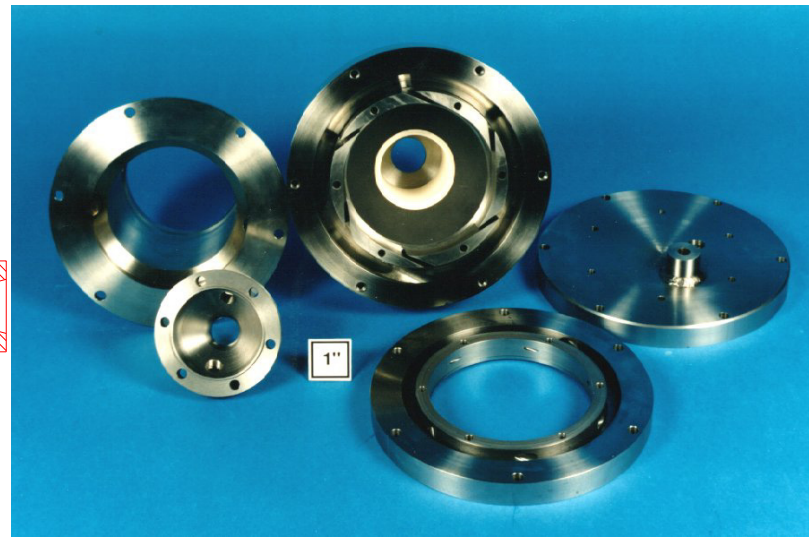


# Pilot-Scale Combustor Operation with Diluent Water

## Cross-section of combustor



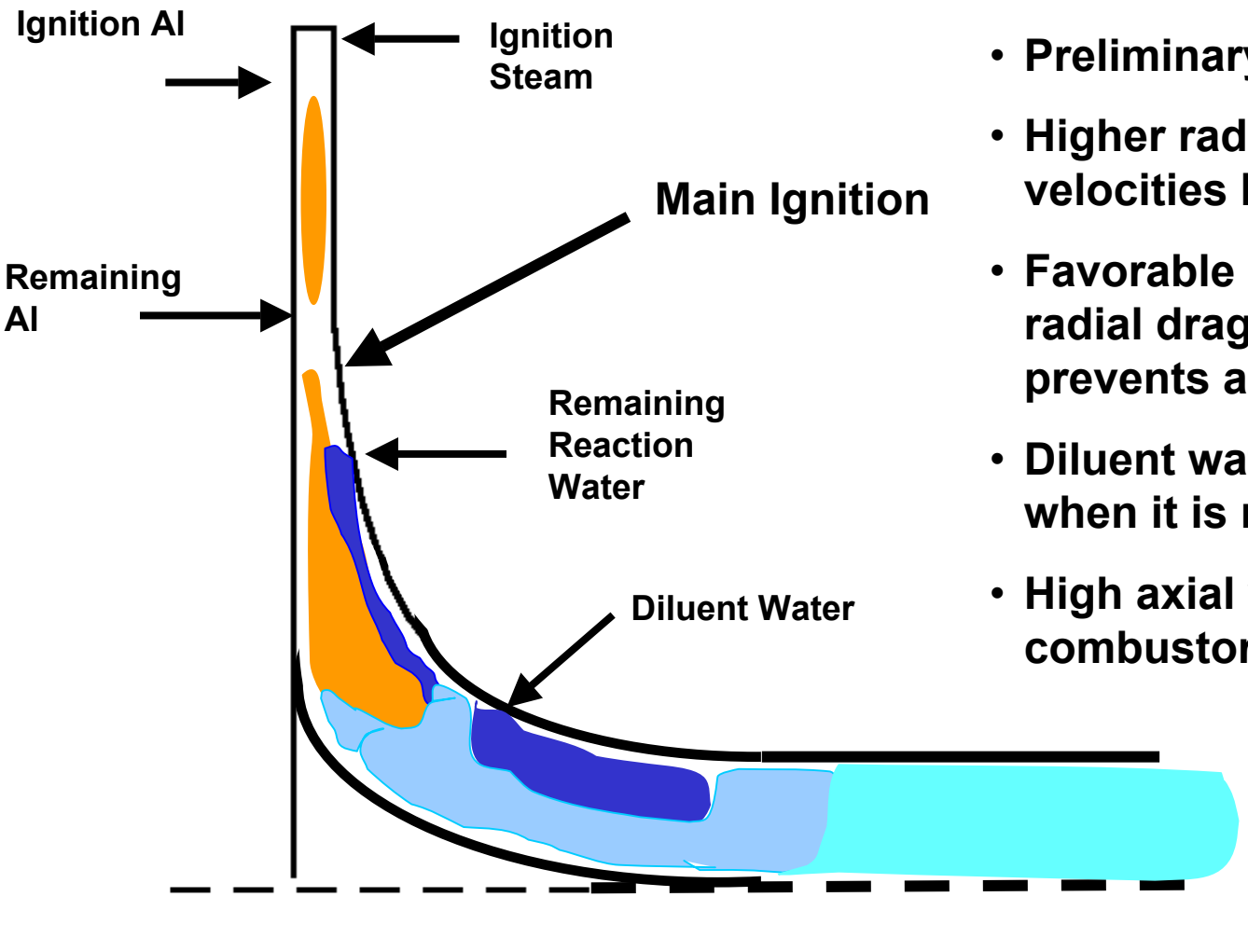
## Hardware elements of combustor




**Lessons learned from previous vortex combustor experience used to develop long endurance vortex combustor design.**

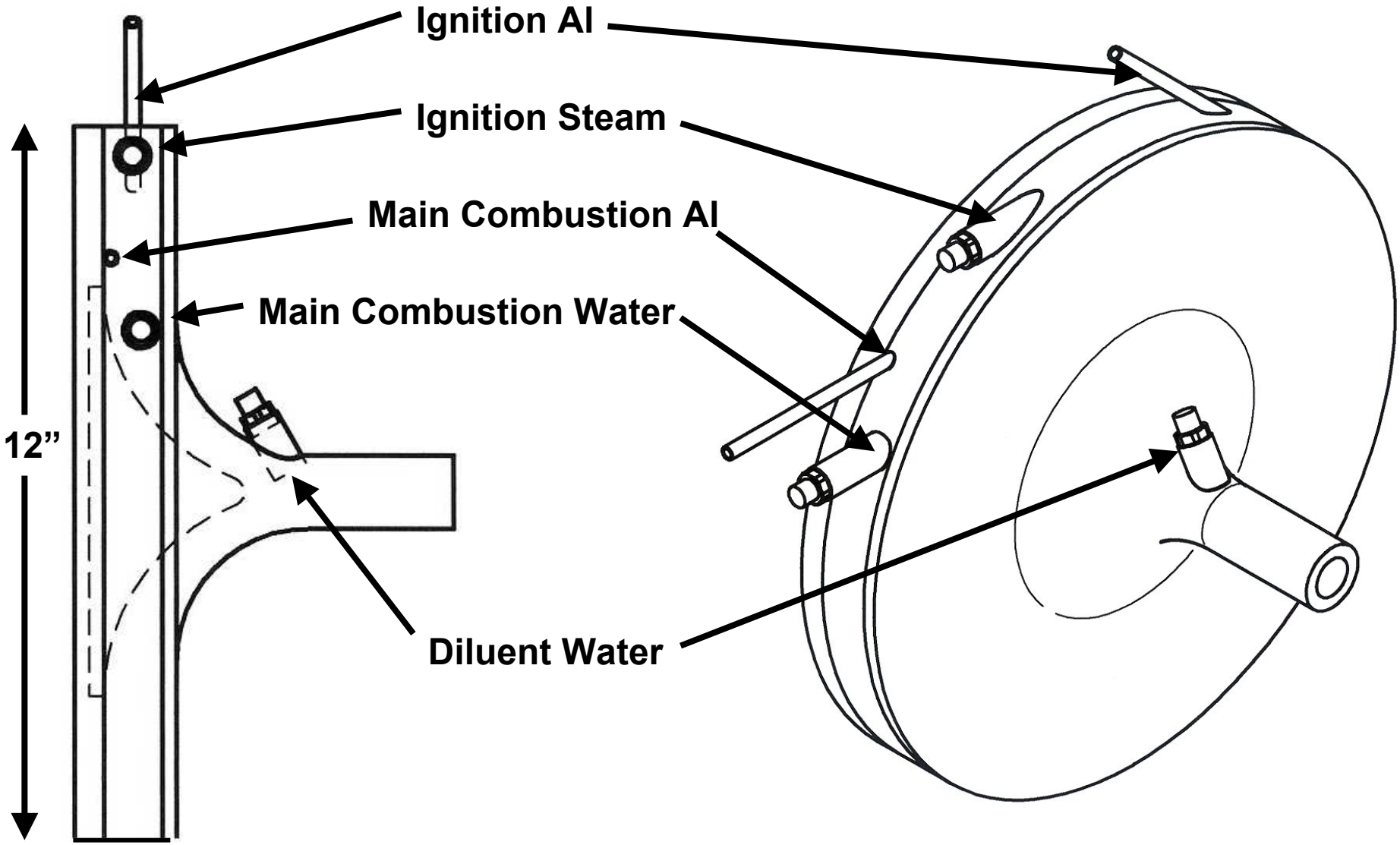
ARL

# Conceptual Sketch of Long Endurance Vortex Combustor

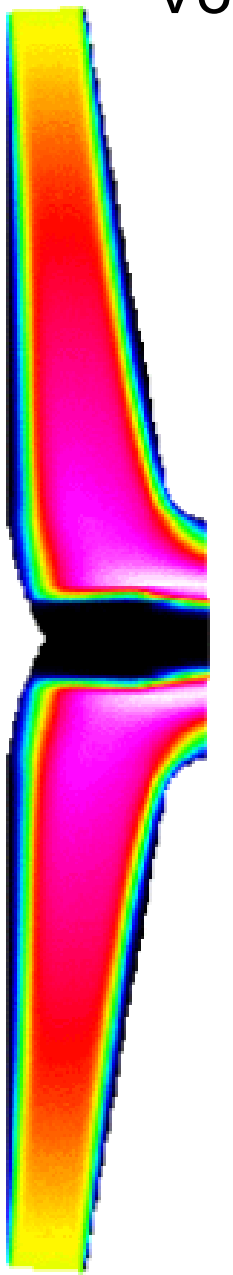


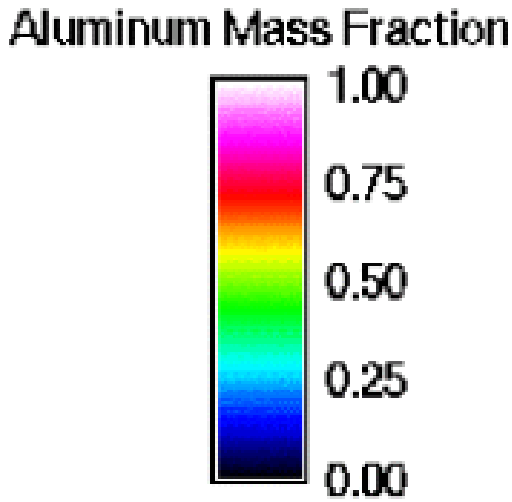

- Preliminary ignition zone
- Higher radial and tangential velocities keep walls clean
- Favorable ratio of centrifugal to radial drag forces ($F_{Cent}$ / $F_{Drag}$ < 1) prevents accumulation
- Diluent water stops vortex flow when it is no longer required
- High axial velocity exiting combustor prevents accumulation

# Long Endurance Combustor Concept



# Vortex-Combustor Modeling






0.5 Inch Injector (Canted 5 degrees)

4 Inch Outer Radius

10 μm particles

15 degree inlet swirl angle

0.2 lbm/sec inlet mass flowrate for aluminum

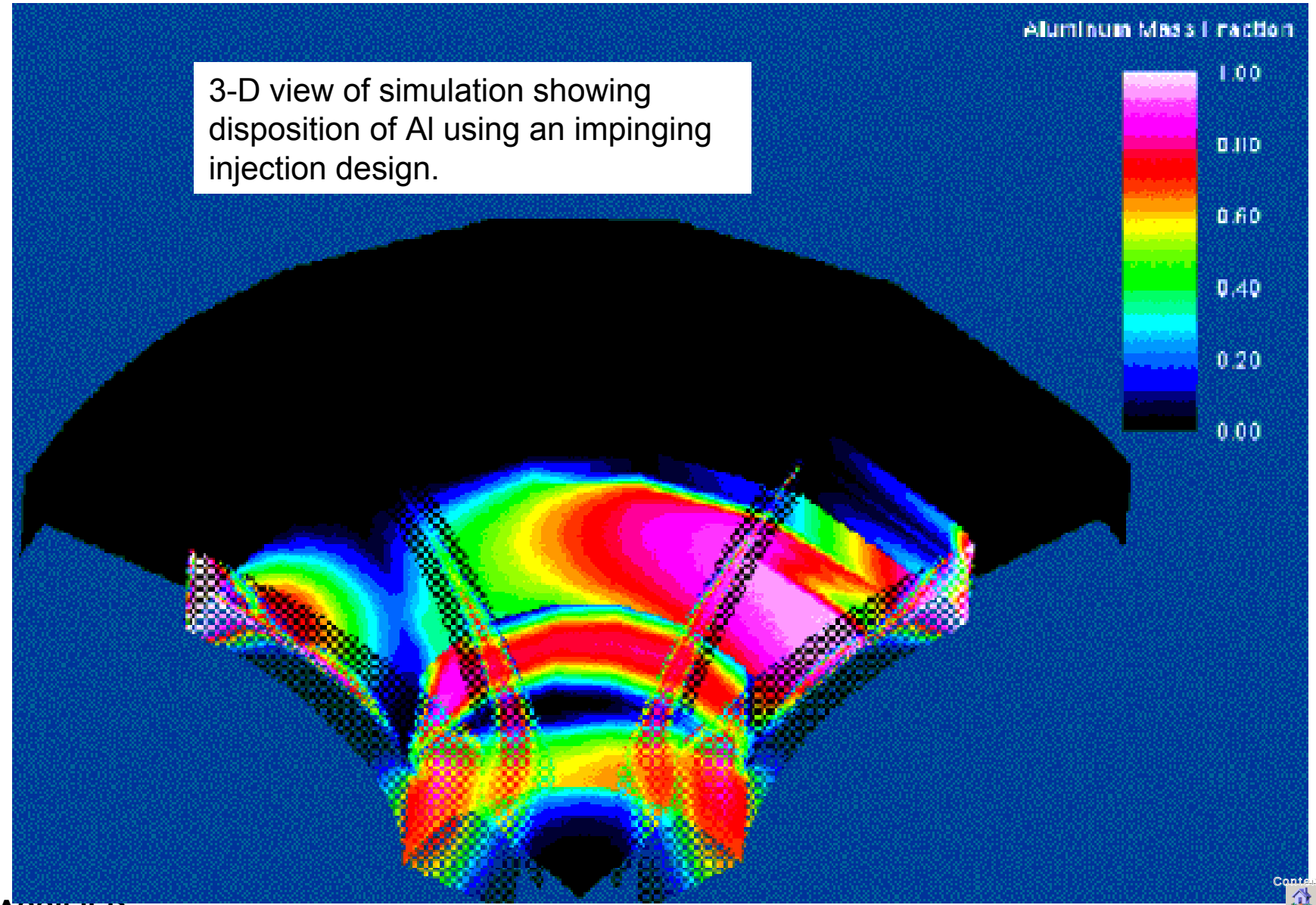
Steam/Aluminum = 1.1

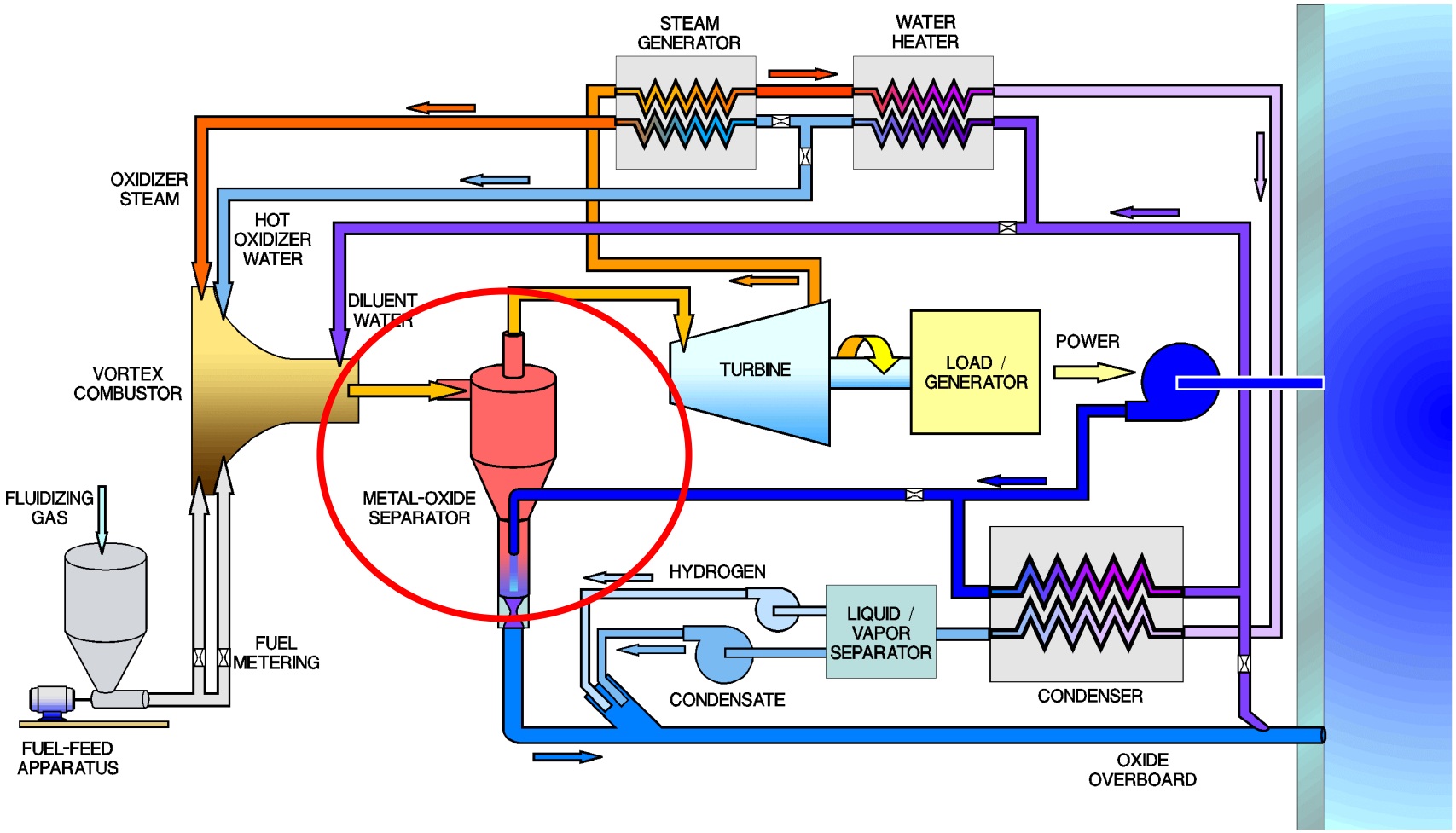
10 degree slope on back wall

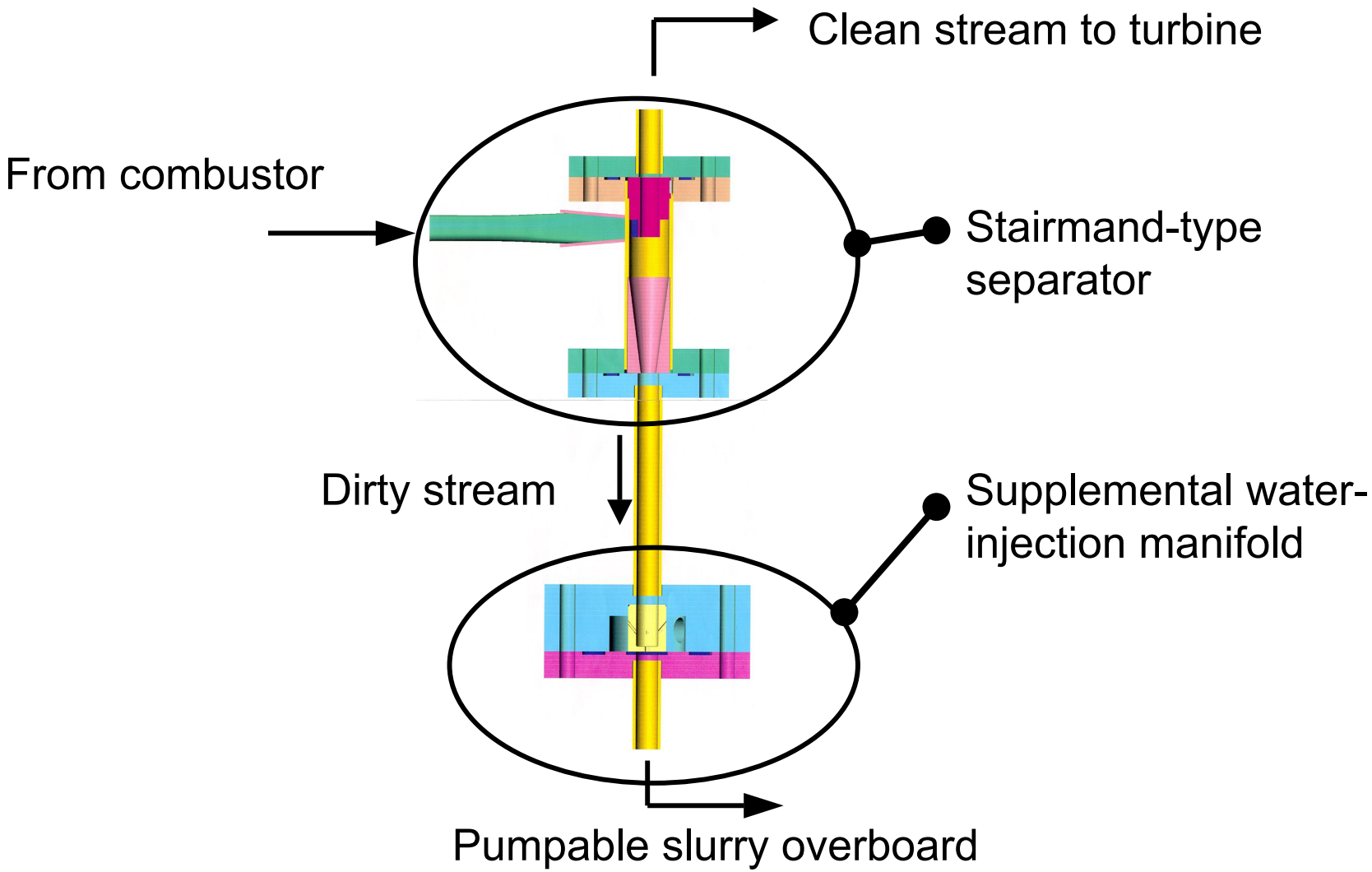
49.1 millisecond residence time to target ignition point

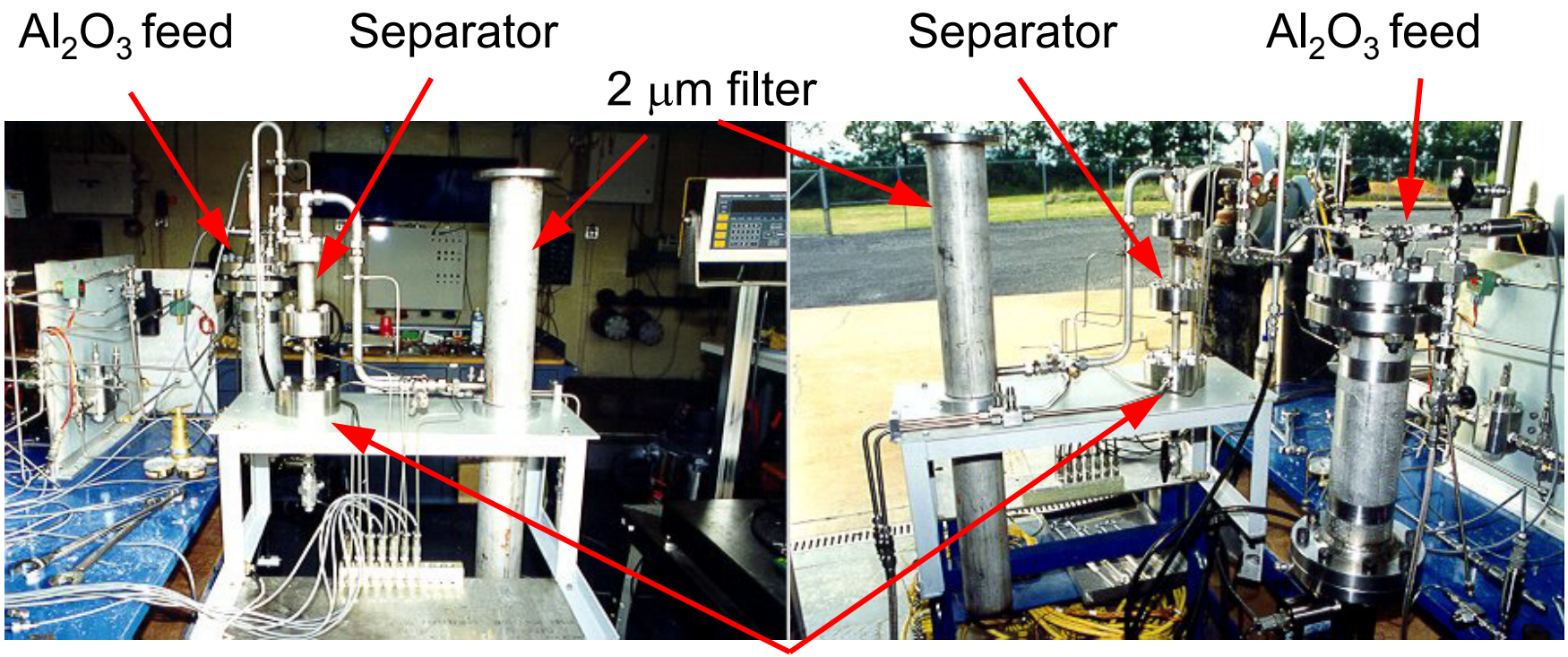
# Vortex-Combustor Modeling

3-D view of simulation showing disposition of Al using an impinging injection design.



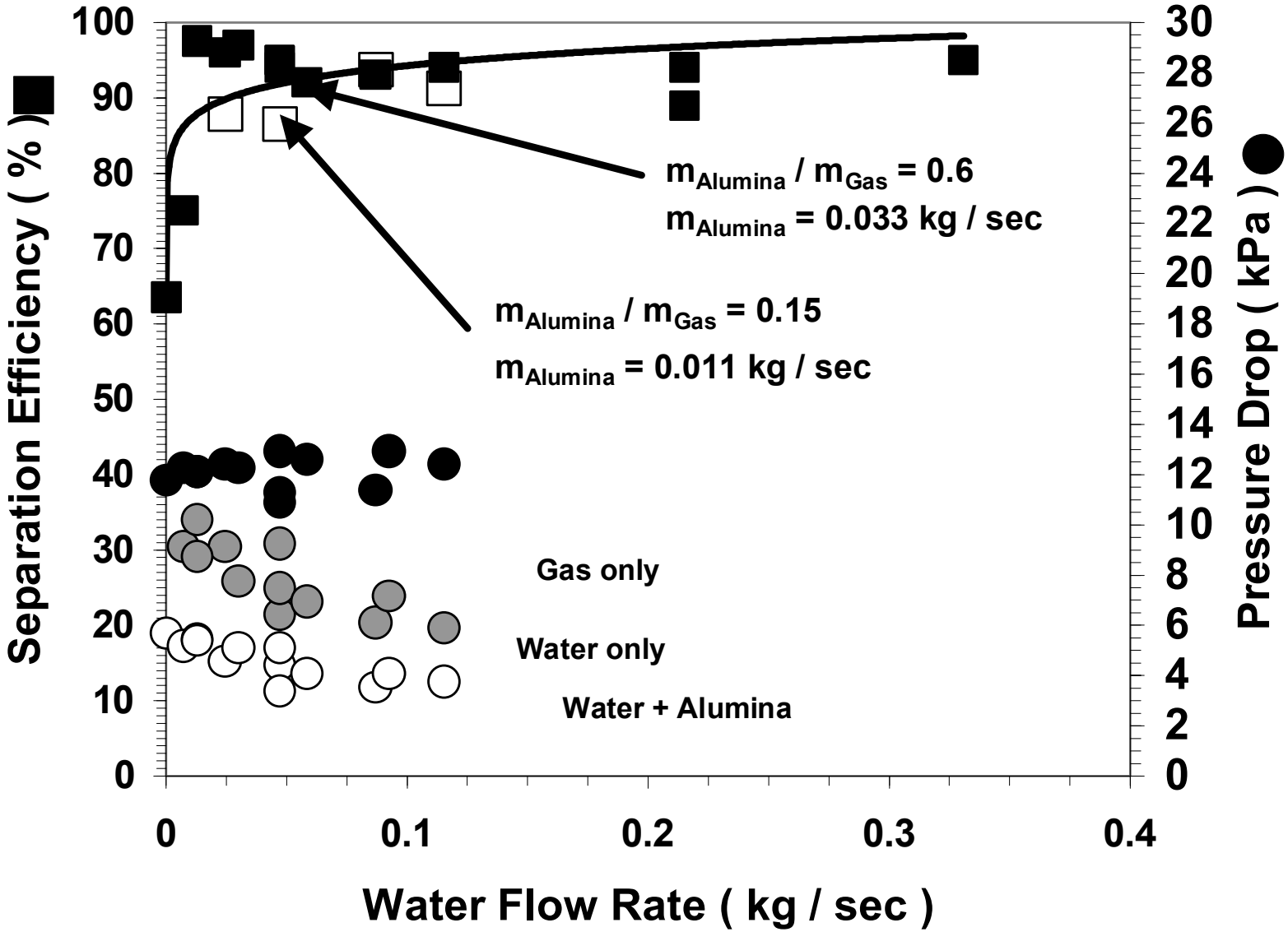

STEAM GENERATOR
WATER HEATER
OXIDIZER STEAM
HOT OXIDIZER WATER
DILUENT WATER
VORTEX COMBUSTOR
TURBINE
LOAD / GENERATOR
POWER
FLUIDIZING GAS
METAL-OXIDE SEPARATOR
HYDROGEN
LIQUID / VAPOR SEPARATOR
CONDENSATE
CONDENSER
FUEL METERING
FUEL-FEED APPARATUS
OXIDE OVERBOARD

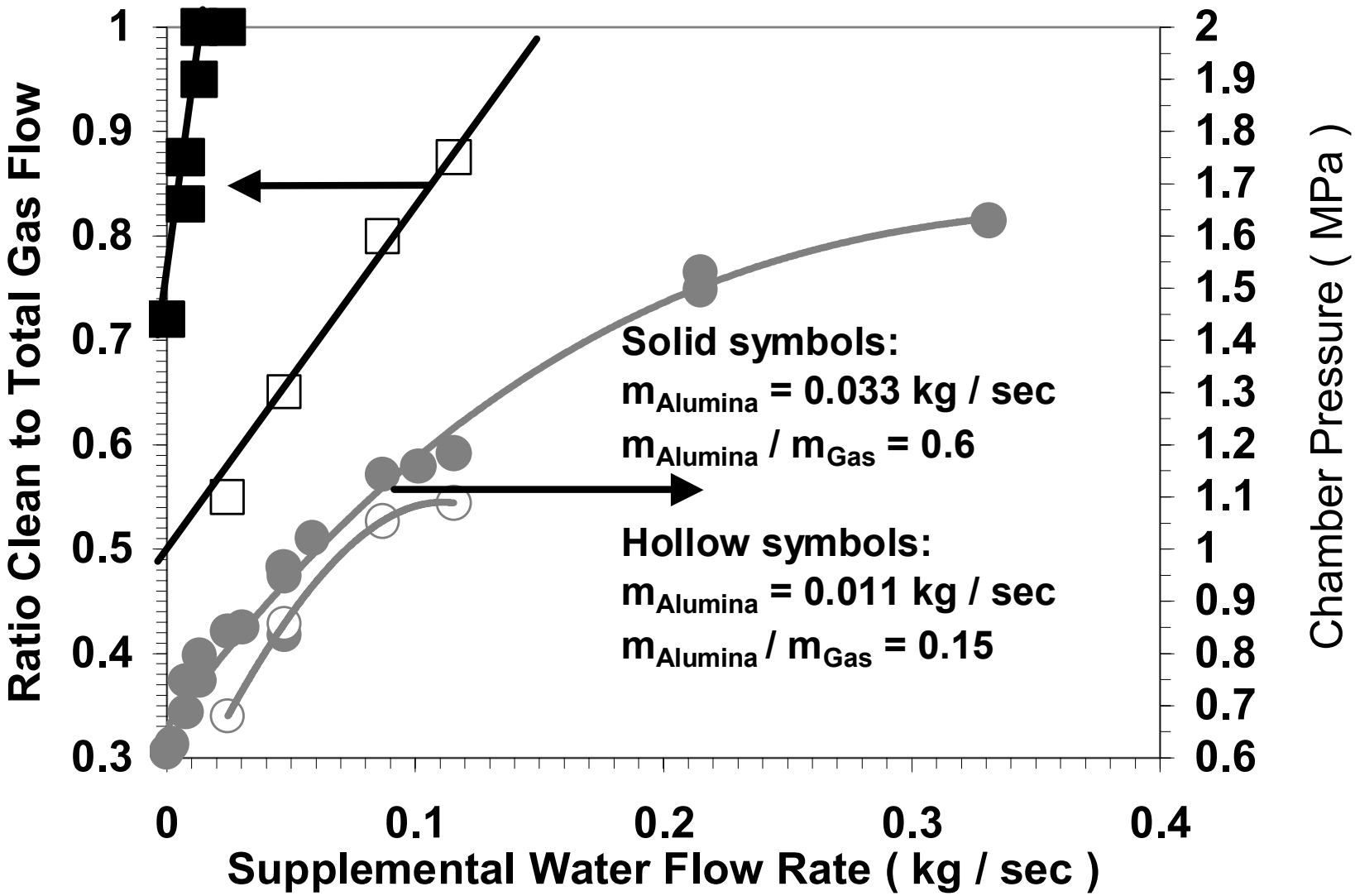

Clean stream to turbine
From combustor
Stairmand-type separator
Dirty stream
Supplemental water-injection manifold
Pumpable slurry overboard

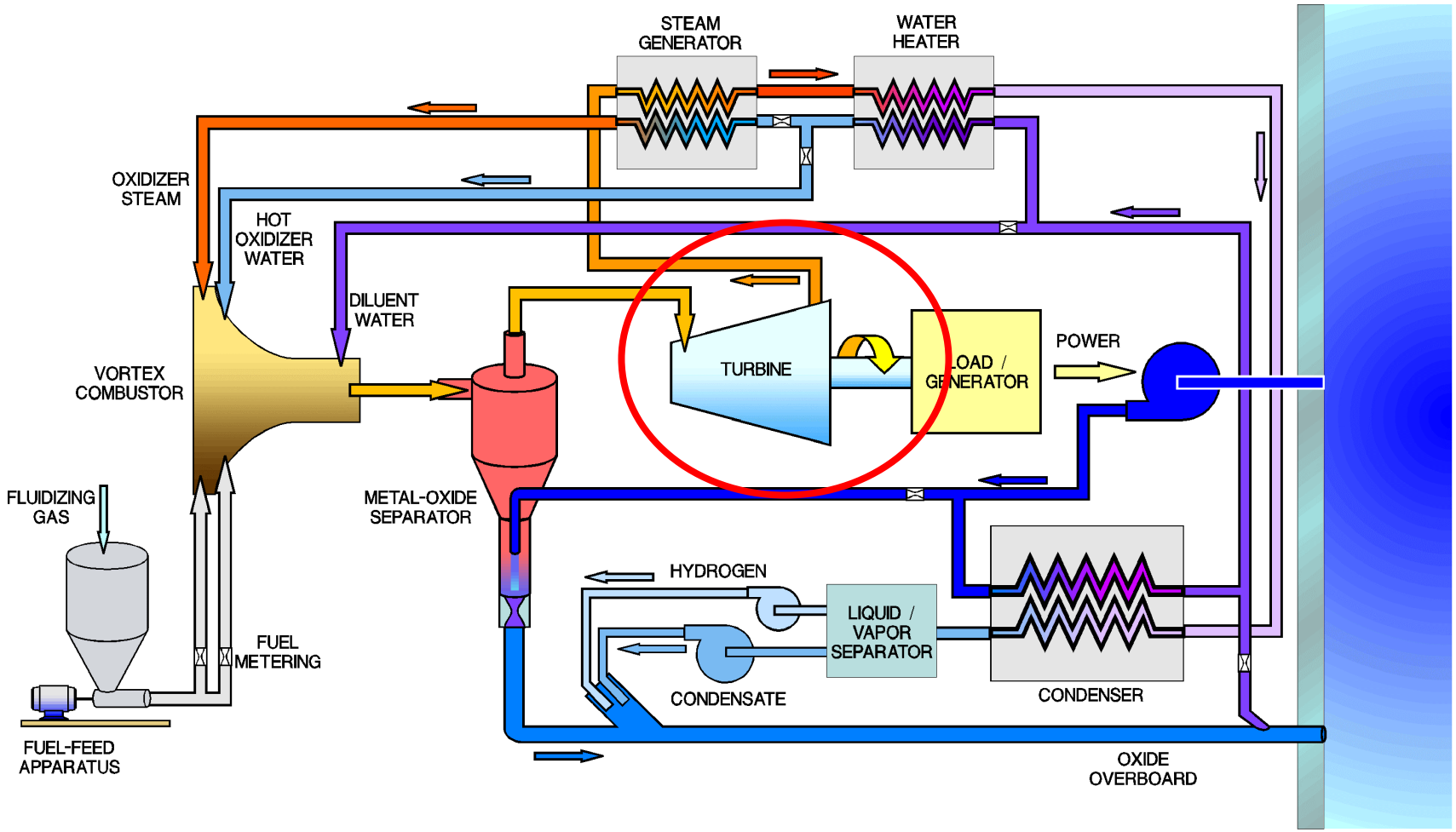


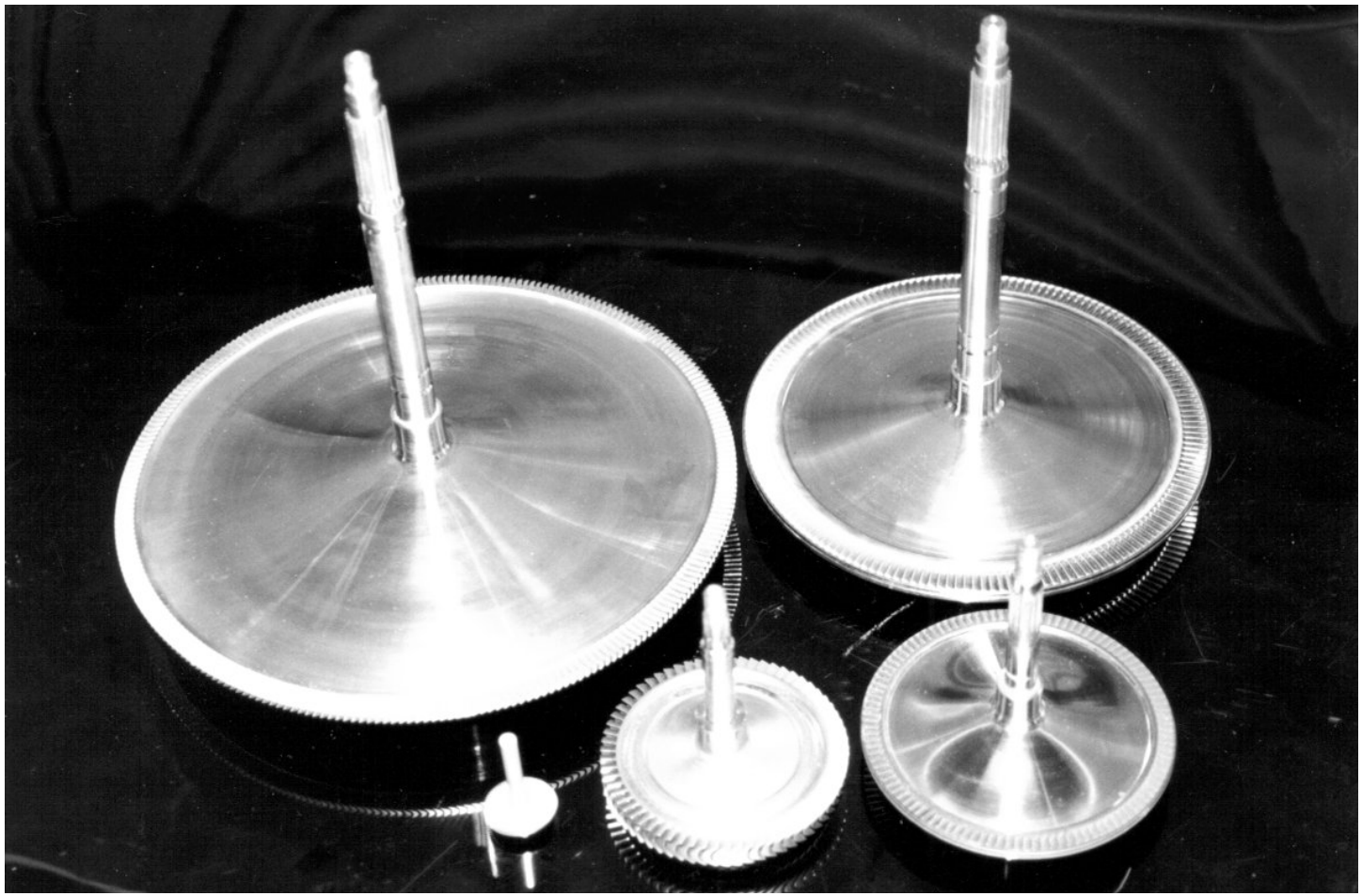

Front view

Rear view


Separation Efficiency ( % )
Pressure Drop ( kPa )
Water Flow Rate ( kg / sec )
100
90
80
70
60
50
40
30
20
10
0
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
$m_{Alumina}$ / $m_{Gas}$ = 0.6
$m_{Alumina}$ = 0.033 kg / sec
$m_{Alumina}$ / $m_{Gas}$ = 0.15
$m_{Alumina}$ = 0.011 kg / sec
Gas only
Water only
Water + Alumina


Ratio Clean to Total Gas Flow
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
Chamber Pressure ( MPa )
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0
0.1
0.2
0.3
0.4
Supplemental Water Flow Rate ( kg / sec )
Solid symbols:
$m_{Alumina}$ = 0.033 kg / sec
$m_{Alumina}$ / $m_{Gas}$ = 0.6
Hollow symbols:
$m_{Alumina}$ = 0.011 kg / sec
$m_{Alumina}$ / $m_{Gas}$ = 0.15


STEAM GENERATOR
WATER HEATER
OXIDIZER STEAM
HOT OXIDIZER WATER
DILUENT WATER
VORTEX COMBUSTOR
TURBINE
LOAD / GENERATOR
POWER
FLUIDIZING GAS
METAL-OXIDE SEPARATOR
HYDROGEN
LIQUID / VAPOR SEPARATOR
CONDENSATE
CONDENSER
FUEL METERING
FUEL-FEED APPARATUS
OXIDE OVERBOARD



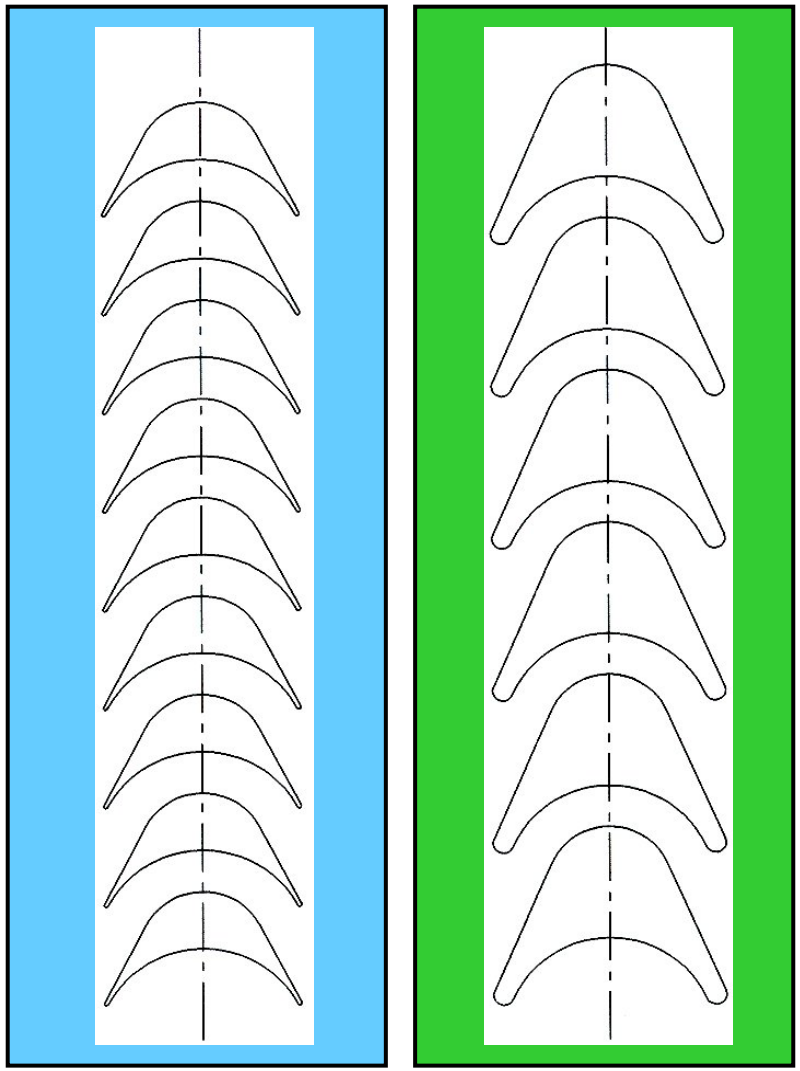
# Impulse Turbine
# High-Speed Assemblies

Heavyweight

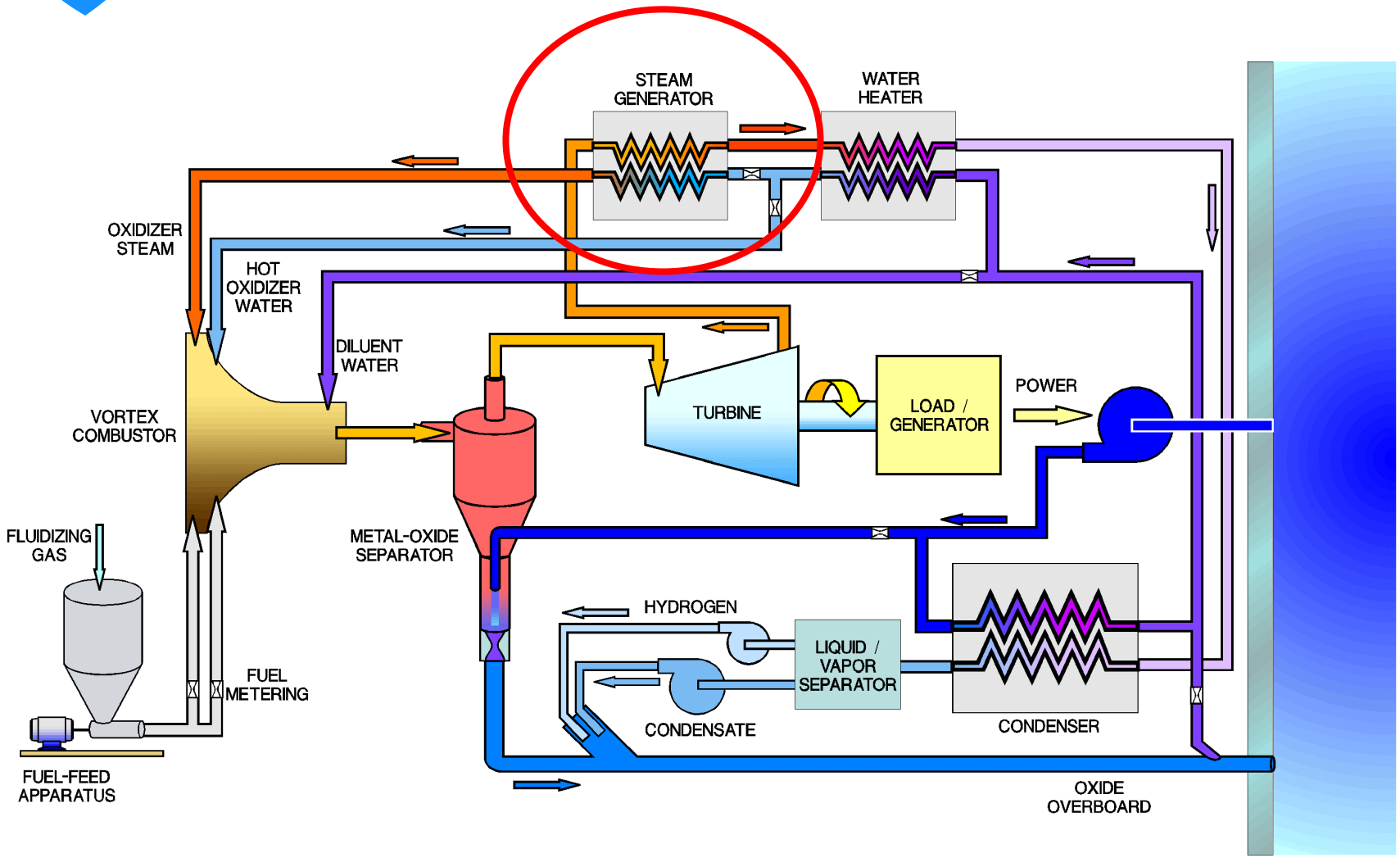
Lightweight

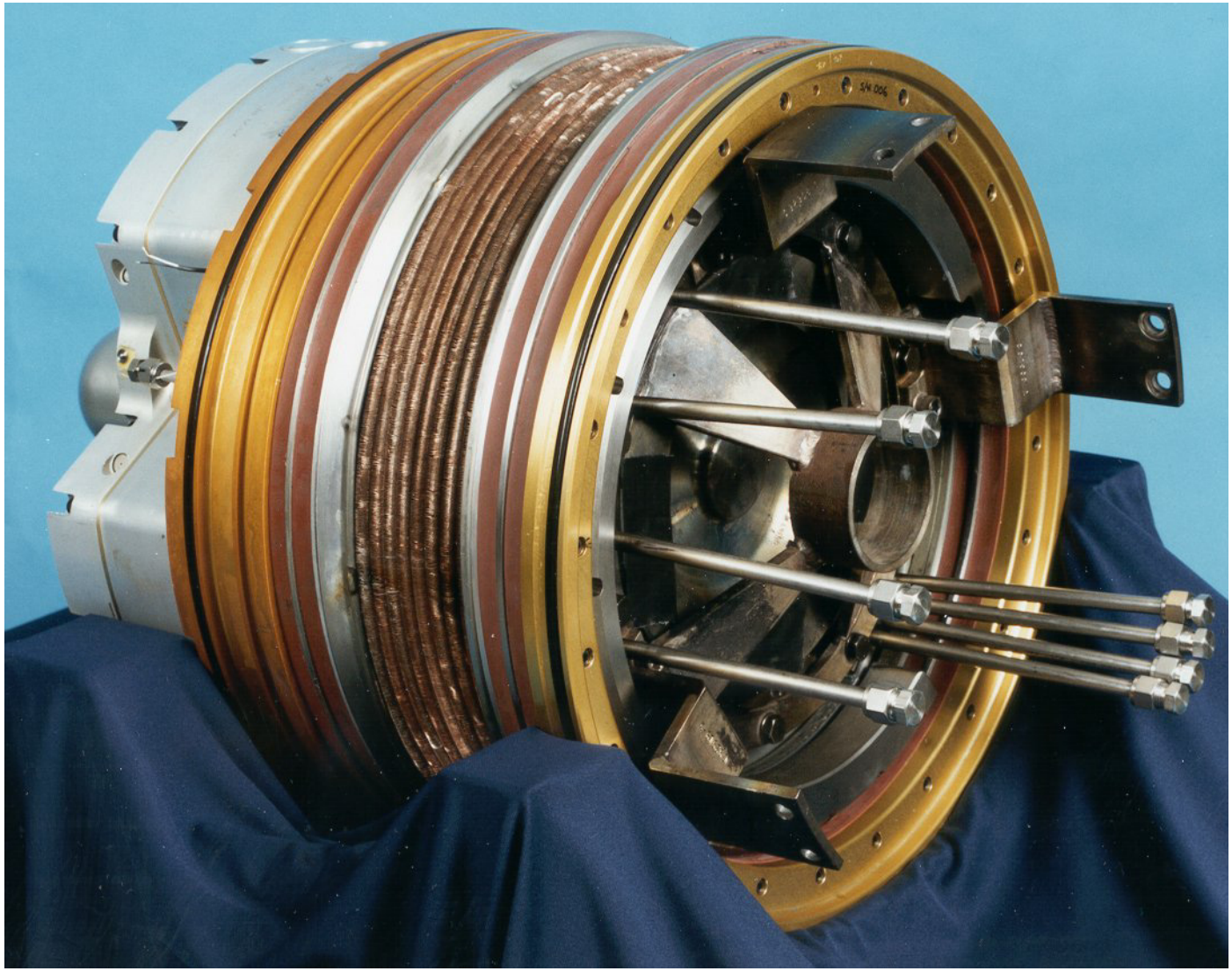
# Turbine Blade Comparison

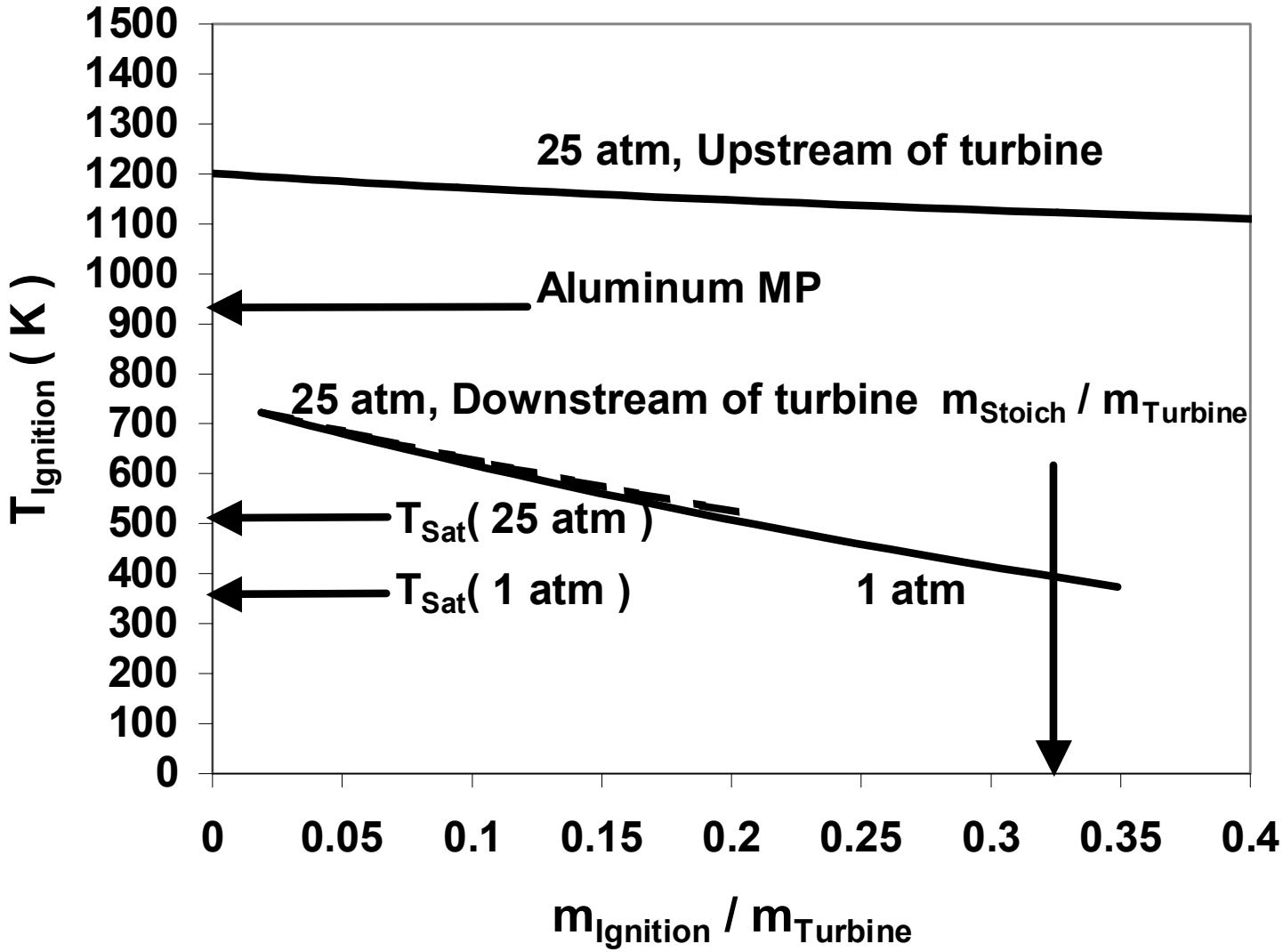
Torpedo Turbine




AUV Turbine


STEAM GENERATOR
WATER HEATER
OXIDIZER STEAM
HOT OXIDIZER WATER
DILUENT WATER
VORTEX COMBUSTOR
TURBINE
LOAD / GENERATOR
POWER
FLUIDIZING GAS
METAL-OXIDE SEPARATOR
HYDROGEN
LIQUID / VAPOR SEPARATOR
CONDENSATE
CONDENSER
FUEL METERING
FUEL-FEED APPARATUS
OXIDE OVERBOARD




1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
T Ignition ( K )
25 atm, Upstream of turbine
Aluminum MP
25 atm, Downstream of turbine m Stoich / m Turbine
T Sat( 25 atm )
T Sat( 1 atm )
1 atm
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
m Ignition / m Turbine

# Summary

- This paper describes a hypothetical seawater-breathing AUV energy system based on the reaction of powdered aluminum.
- The reaction of aluminum with seawater offers improvement in energy density that could revolutionize the ability for long duration operation underwater.
- Although the system is hypothetical, the critical components are currently undergoing active engineering research and development.
- The level of technical maturity of the critical components suggest that the development of a next-generation aluminum-seawater combustion system for AUV applications is feasible.