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W. A. Couch, Editor

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KINEMATIC STIRLING ENGINE STATUS
FOR
SOLAR THERMAL ELECTRIC SYSTEMS*

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ABSTRACT

The Department of Energy's (DOE) Solar Thermal Program has as one of its program tasks the development and evaluation of conversion devices that are applicable to solar thermal electric systems. To date, the primary research and development activities have involved the dish-electric concept, which consists of a heat engine, solar receiver, and generator combined to form a power conversion assembly (PCA), which is then mounted at the focal plane of a parabolic dish concentrator. The solar thermal program has identified the Stirling cycle heat engine as the conversion device with the most potential for meeting the program goals for annual engine efficiency (41%), reliability (50,000 hour life), and cost ($300/kWe installed, 1984 $).

Of the available Stirling heat engines the United Stirling 4-95 MKII automotive engine has received the most extensive development for dish-electric systems. The 4-95 was modified for the solar application by incorporating a direct-absorbing solar receiver with the engine heater heads, adapting the power control scheme, and redesigning the lubrication system because of the inverted operation. With DOE funding, the Advanco Corporation used this modified engine in a dish-electric demonstration project called Vanguard. This system demonstrated an overall net system conversion efficiency, solar-to-electric, of 29.4%. This is the highest conversion efficiency achieved by any solar system technology. However, because this engine was originally designed as an automotive engine, its design life is limited to 3500 hours (100,000 miles) before major overhauls. The directly illuminated heater heads/solar receiver and complex power control system were the cause of problems during the demonstration. McDonnell Douglas Corporation utilized a similar United Stirling engine for a dish-electric system that it developed. The system demonstrated conversion efficiencies of 30%. However, again, the limitations of the automotive engine design caused problems for a reliable solar application.

To advance the Stirling technology toward longer life and commercialization, Sandia recently acquired a Stirling Thermal Motors, Inc. (STM) kinematic Stirling engine, STM4-120 for evaluation. This is a four-cylinder engine

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* This work was performed at Sandia National Laboratories, operated for the U.S. Department of Energy under contract number DE-AC04-76DP000789.

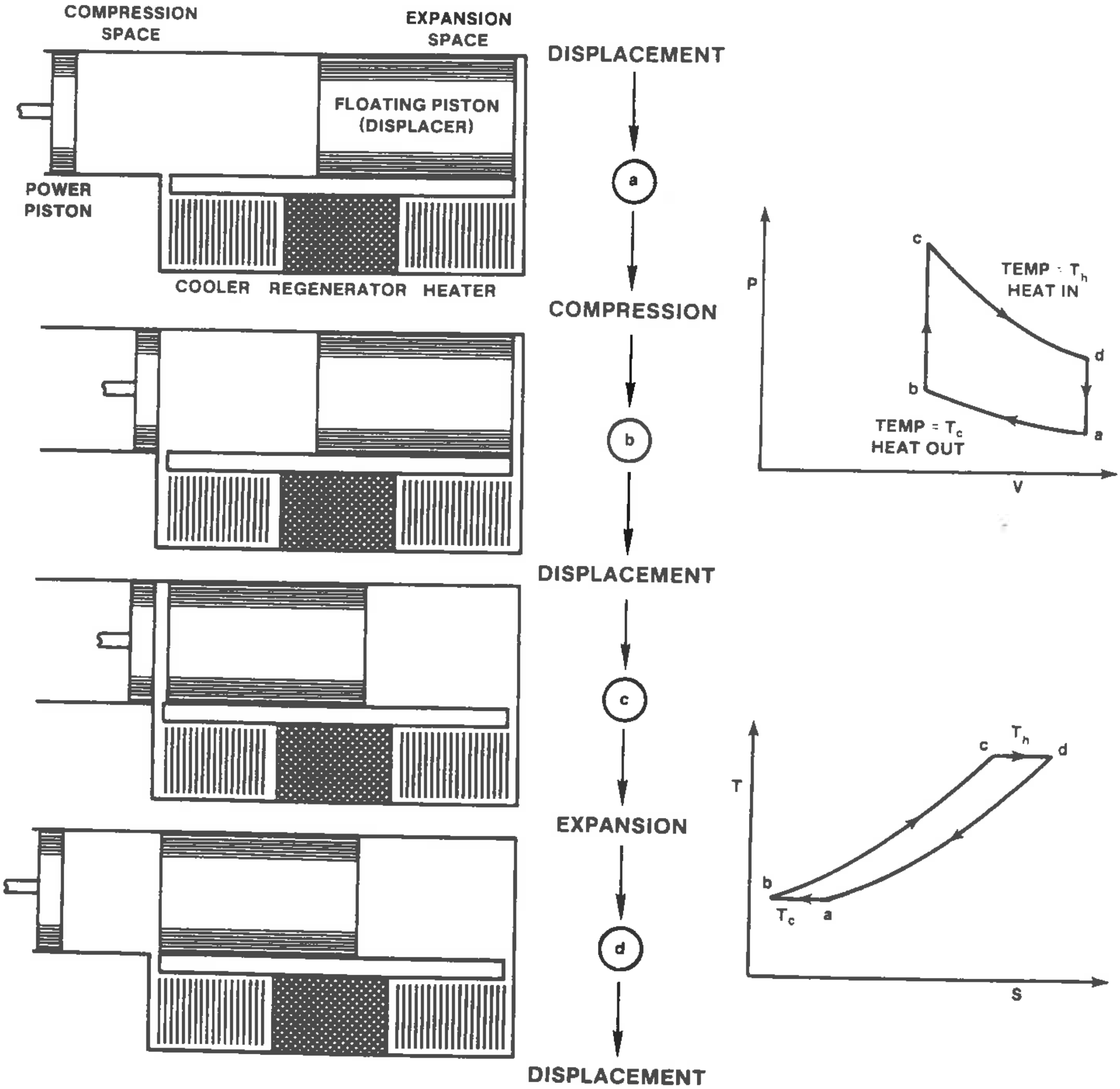
with a double-acting piston design. It is nominally rated for 25 kW of shaft power output while operating at a heater head temperature of 800°C. STM has demonstrated 23 kW of shaft power with a conversion efficiency of 40% at a heater temperature of 785°C. This engine was designed from the outset to be a long-life machine --50,000 hours before major overhauls. To obtain this life STM has incorporated a pressurized crankcase (increase rod seal life), variable swashplate (efficient and reliable power control), and heat pipe technology (isothermal operation for better efficiency) into its engine. These features give the STM4-120 the potential to achieve the solar thermal program's operation and maintenance goals and increased system efficiencies.

Sandia's Solar Thermal Electric Technology and Testing Divisions will be bench testing the STM4-120 for performance and reliability characteristics at Sandia's recently constructed Engine Test Facility. Initial tests will utilize gas combustion as the heat source to operate the engine. The complete mapping of the engine's performance, ie. power and efficiency, will be a major task in the test procedure and reliability issues will be closely monitored. Sandia will be evaluating the engine through FY89 and FY90. In later programs, Sandia will incorporate the engine with a solar receiver for actual 'on-sun' testing.

WHY
STIRLING CYCLE
FOR DISTRIBUTED RECEIVER SYSTEMS

- High cycle efficiency (over 40%)
- Continuous external heating, efficient, hybrid
- High power to weight ratio (~18 kg/kWe)
- Potential for long life and high reliability

STIRLING CYCLE



Sandia National Laboratories

Solar Energy

STM

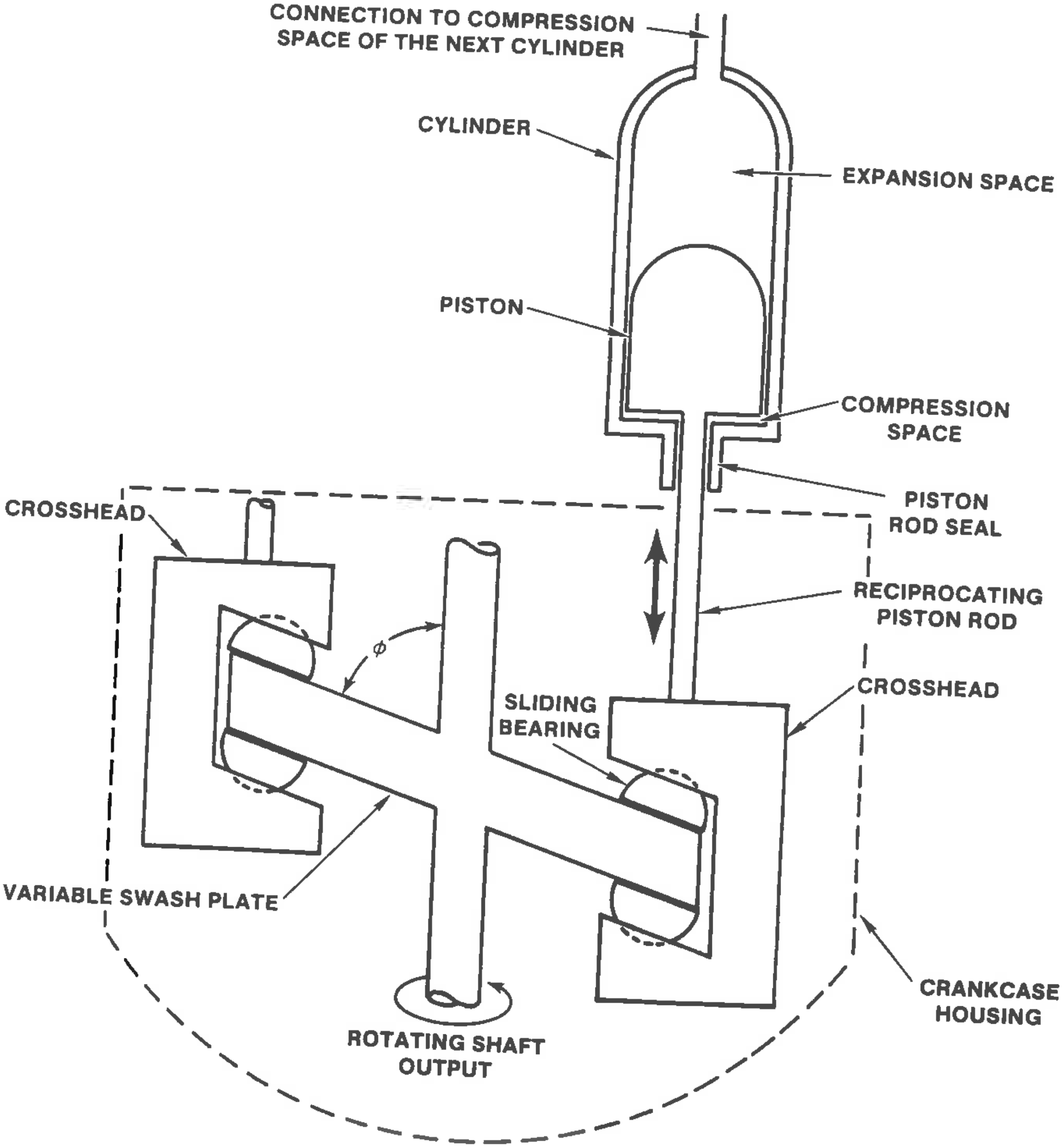
WHY
STIRLING THERMAL MOTORS
KINEMATIC STIRLING
FOR DISTRIBUTED RECEIVER SYSTEMS

- **Cycle efficiency, 40-45% @ 1800 rpm, 25 kWe**
  40-45% @ 2800 rpm, 40 kWe
- **Heat pipe input, flexibility of receiver design**
- **Pressurized crankcase, eliminates ΔP across rod seals**
- **Variable swashplate drive, compact control mechanism**

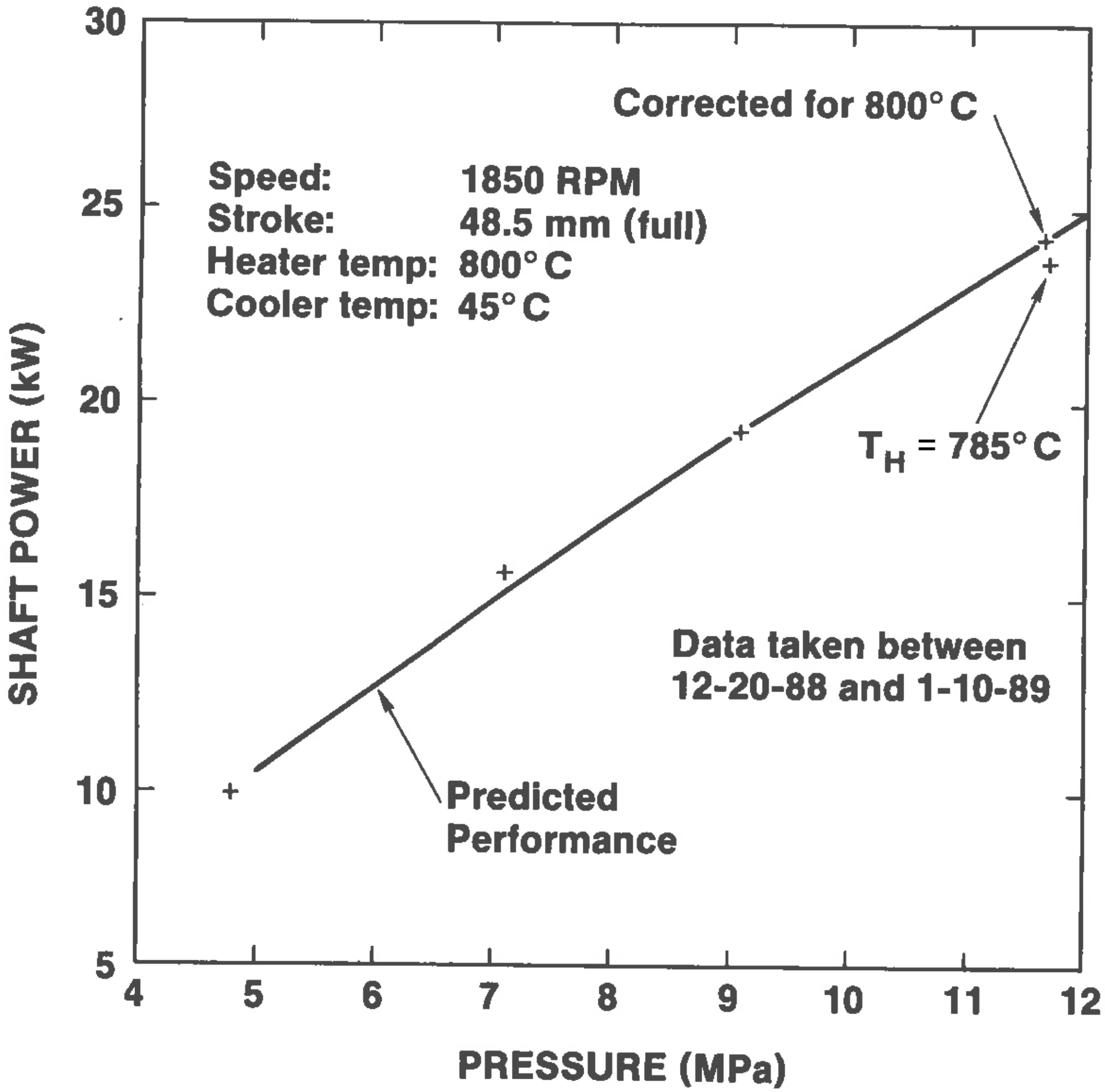
STM4-120
IMPORTANT FEATURES AND PARAMETERS

Arrangement:	Four double-acting cylinders symmetrically arranged about a common axis. One heat exchanger assembly per cylinder.
Bore:	56 mm
Maximum Stroke:	48 mm
Overall Length:	635 mm
Cross-sectional Dimensions:	Largest cross section is 300 mm in diameter
Total Estimated Weight:	75 kg
Working Fluid:	Helium
Mean Cycle Pressure:	11 MPa
Heater Temperature:	800° C
Power Control:	Piston stroke variation by means of a variable swashplate with a maximum angle of 22°
Heat Transport:	Sodium heat pipe
Gas Containment:	Crankcase pressurized to mean cycle pressure and sealed with a rotating shaft seal
Oil Containment:	Reciprocating rod oil scrapers
Materials:	Iron-based CRM-6D, CG-27 heater tubes

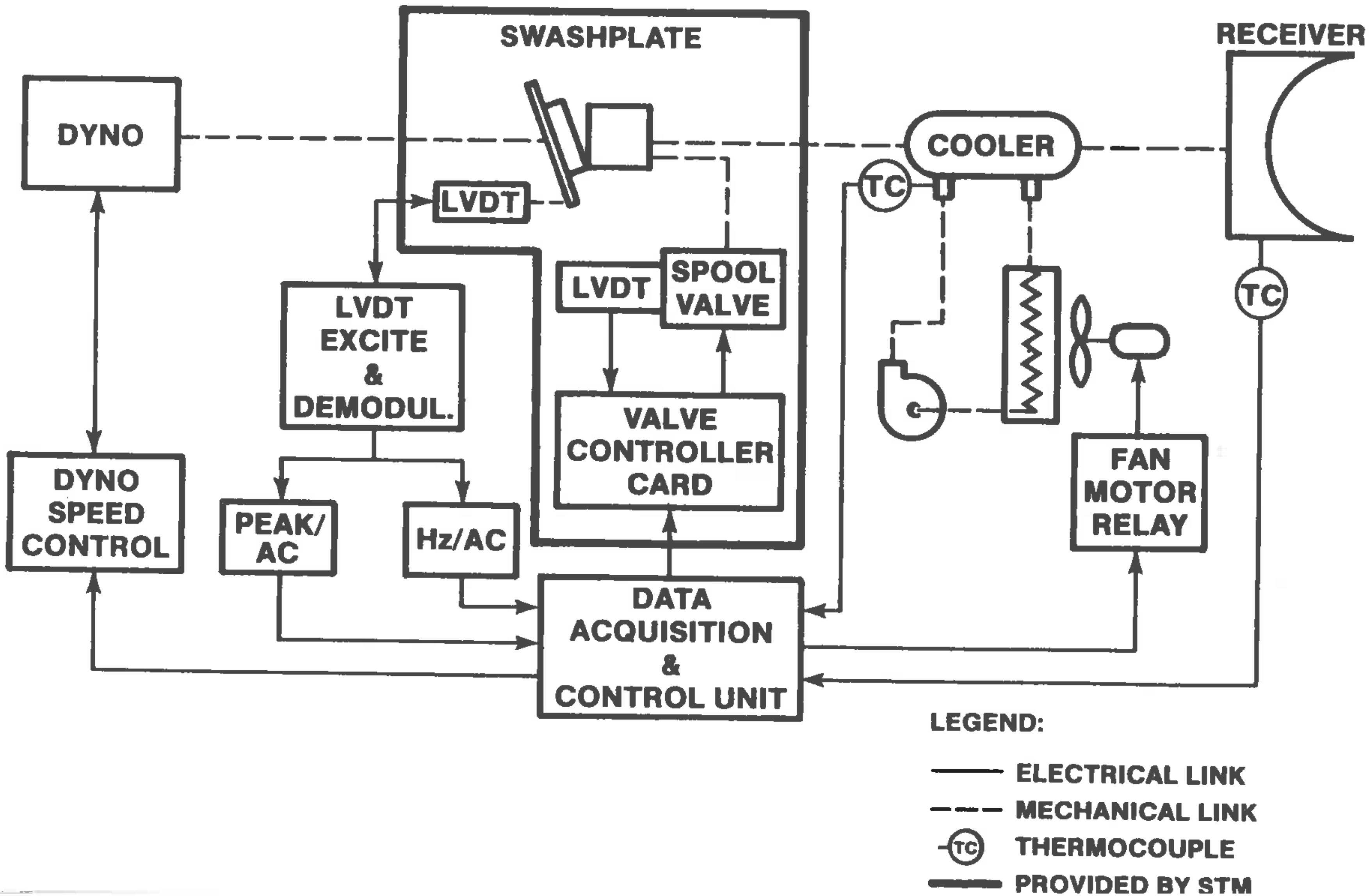
STM 4-120 CROSS-SECTION

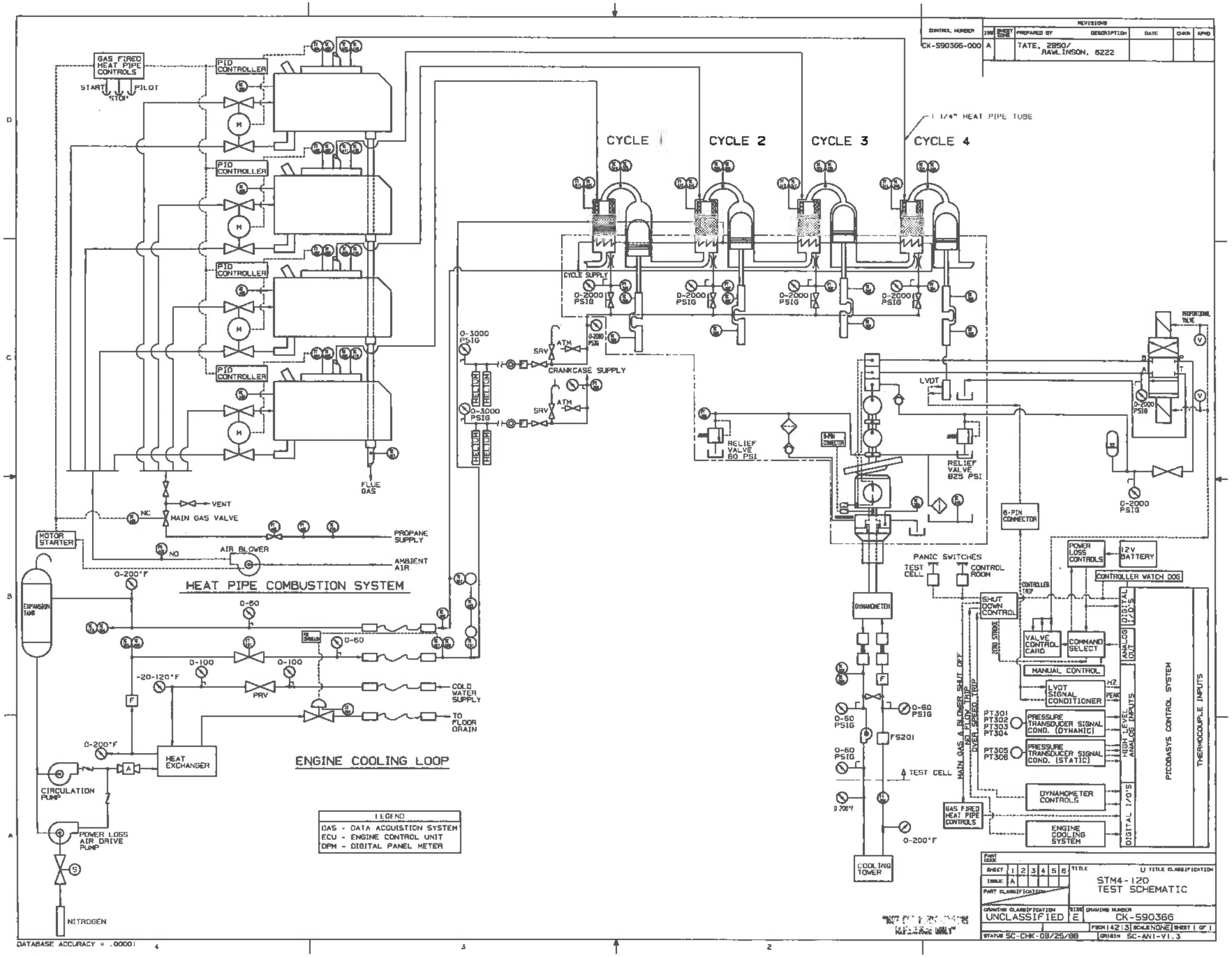


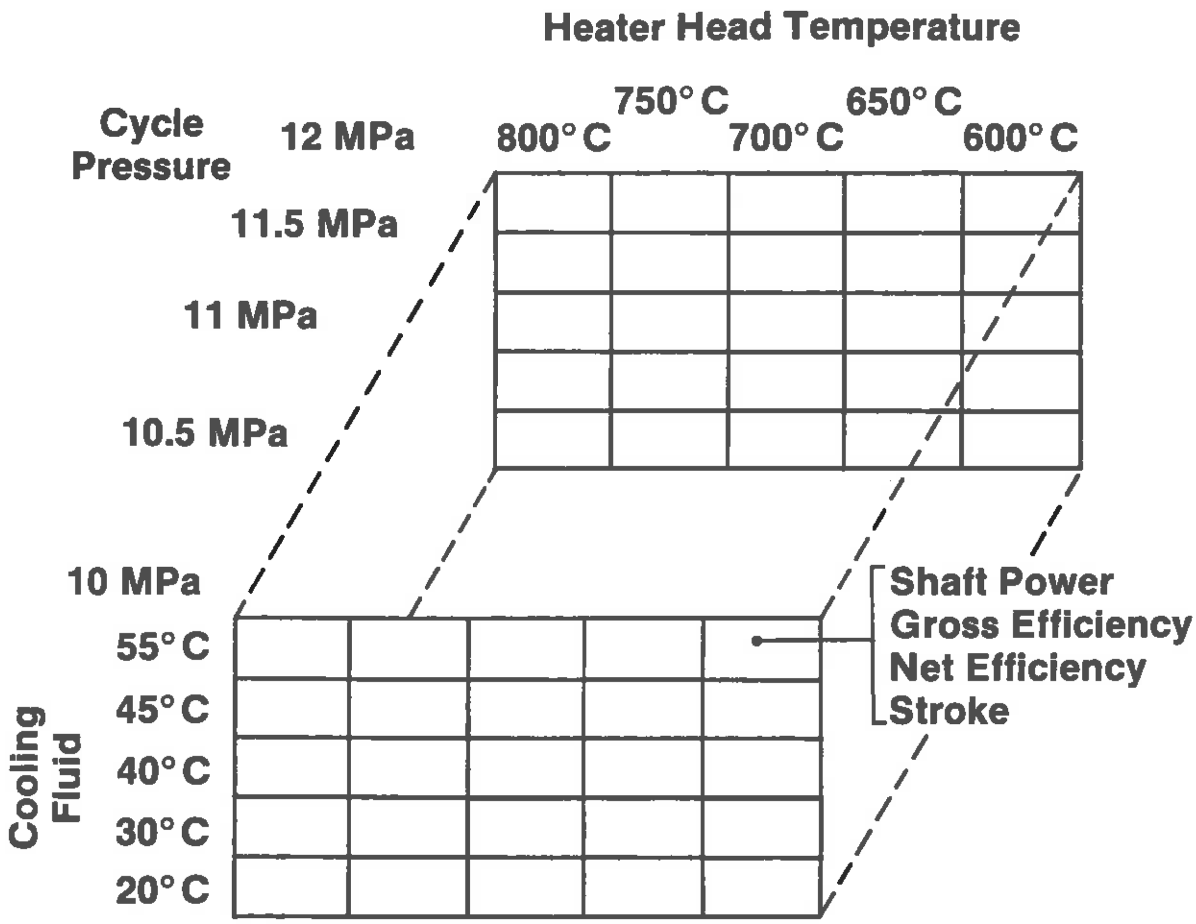
STM4-120 PERFORMANCE



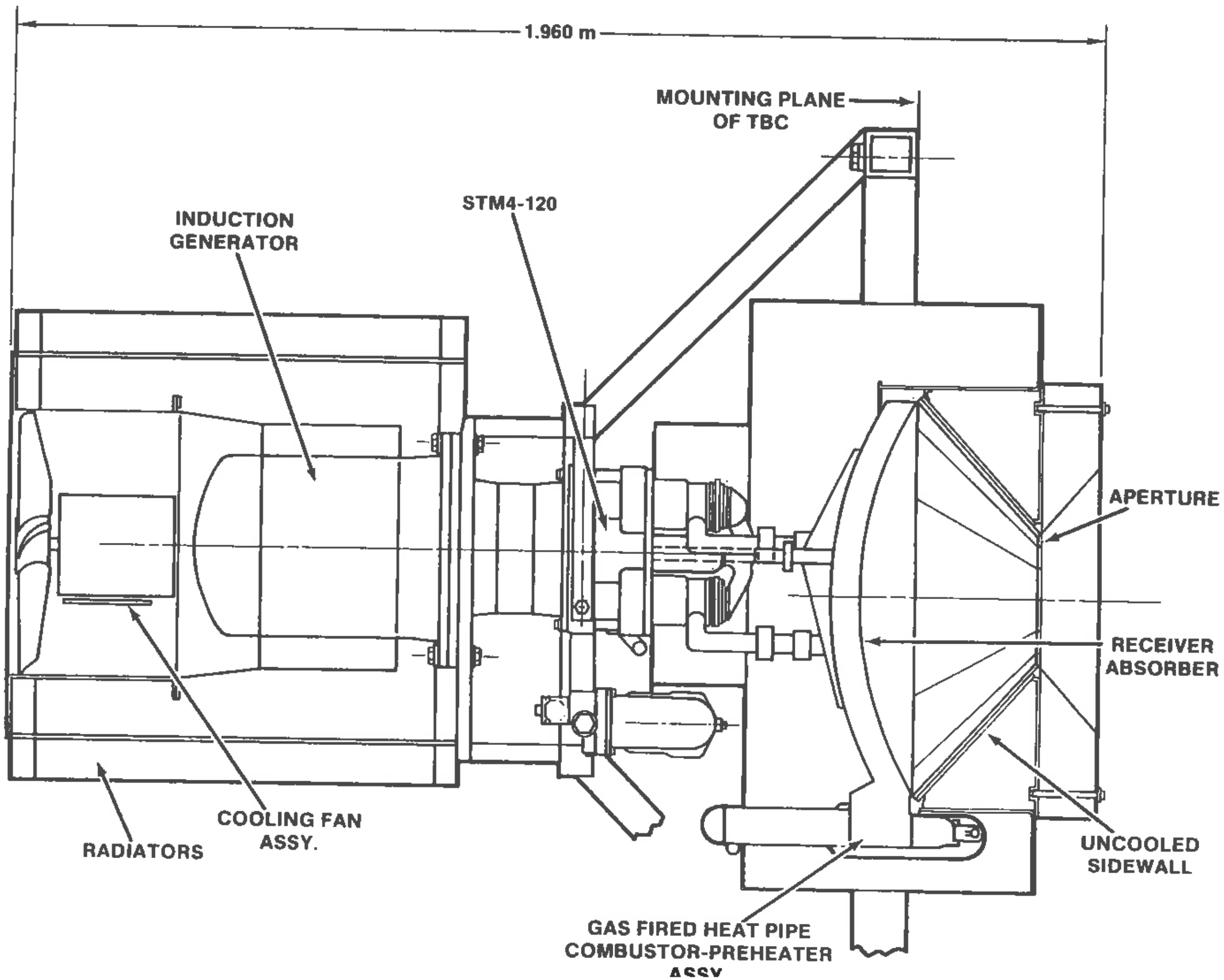
STM4-120 CONTROLS




GAS FIRED HEAT PIPE CONTROLS
START
STOP
PILOT
PID CONTROLLER
1 1/4" HEAT PIPE TUBE
CYCLE 1
CYCLE 2
CYCLE 3
CYCLE 4
CYCLE SUPPLY
0-2000 PSIG
0-3000 PSIG
SRV
ATM
CRANKCASE SUPPLY
HELIUM
FLUE GAS
VENT
NC
MAIN GAS VALVE
PROPANE SUPPLY
MOTOR STARTER
NO
AIR BLOWER
AMBIENT AIR
HEAT PIPE COMBUSTION SYSTEM
EXPANSION TANK
0-200°F
0-60
0-100
-20-120°F
PRV
COLD WATER SUPPLY
TO FLOOR DRAIN
HEAT EXCHANGER
ENGINE COOLING LOOP
CIRCULATION PUMP
POWER LOSS AIR DRIVE PUMP
NITROGEN
LEGEND
DAS - DATA ACQUISITION SYSTEM
ECU - ENGINE CONTROL UNIT
DPM - DIGITAL PANEL METER
RELIEF VALVE 60 PSI
RELIEF VALVE 825 PSI
LVDT
6-PIN CONNECTOR
PANIC SWITCHES
TEST CELL
CONTROL ROOM
DYNAMOMETER
0-60 PSIG
FS201
TEST CELL
COOLING TOWER
POWER LOSS CONTROLS
12V BATTERY
CONTROLLER WATCH DOG
SHUT DOWN CONTROL
VALVE CONTROL CARD
COMMAND SELECT
MANUAL CONTROL
LVDT SIGNAL CONDITIONER
PT301 PT302 PT303 PT304
PRESSURE TRANSDUCER SIGNAL COND. (DYNAMIC)
PT305 PT306
PRESSURE TRANSDUCER SIGNAL COND. (STATIC)
DYNAMOMETER CONTROLS
ENGINE COOLING SYSTEM
GAS FIRED HEAT PIPE CONTROLS
MAIN GAS & BLOWER SHUT OFF
NO FLOW TRIP
OVER SPEED TRIP
DIGITAL I/O'S
ANALOG OUT
HIGH LEVEL ANALOG INPUTS
PICOBASYS CONTROL SYSTEM
THERMOCOUPLE INPUTS
CK-S90366-000
TATE, 2850/ RAWLINSON, 6222
STM4-120 TEST SCHEMATIC
UNCLASSIFIED
CK-S90366
STATUS SC-CHK-08/25/88
ORIGIN SC-ANI-V1.3
DATABASE ACCURACY = .00001


Heater Head Temperature
750° C
650° C
800° C
700° C
600° C
Cycle Pressure
12 MPa
11.5 MPa
11 MPa
10.5 MPa
10 MPa
55° C
45° C
40° C
30° C
20° C
Cooling Fluid
Shaft Power
Gross Efficiency
Net Efficiency
Stroke

STM4-120 STIRLING ENGINE HYBRID REFLUX HEAT-PIPE RECEIVER POWER CONVERSION MODULE



STATUS OF DOE/NASA ADVANCED STIRLING CONVERSION SYSTEMS (ASCS) PROGRAM

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Cleveland, Ohio 44135

ABSTRACT

The Department of Energy's (DOE) Solar Thermal Technology Program, Sandia National Lab. (SNLA) is evaluating heat engines for terrestrial Solar Distributed Heat Receivers. The Stirling engine has been identified by SNLA as one of the most promising engines for terrestrial applications. The potential to meet DOE's goals for performance and cost can be met by the free-piston Stirling engine.

The NASA Lewis Research Center (LeRC) is conducting Stirling activities which are directed toward a dynamic power source for the space application. Space power systems requirements include high reliability, very long life, low vibration and high efficiency. The free-piston Stirling engine has the potential for future high power space conversion systems, either nuclear or solar powered. Although both applications, terrestrial and space power, appear to be quite different, their requirements complement each other.

NASA LeRC is providing management for an Advanced Stirling Conversion System (ASCS) Project through a cooperative Interagency Agreement with DOE. Parallel contracts were completed in 1987 by Mechanical Technology Inc. (MTI) of Latham, NY and Stirling Technology Company (STC) of Richland, WA for the conceptual designs of an ASCS. Each design featured a free-piston Stirling engine, a liquid metal heat pipe receiver, and a means to provide about 25 kW of electric power to a utility grid while meeting DOE's long term performance and cost goals.

The MTI design incorporates a linear alternator to directly convert the solar energy to electricity while STC generates electrical power indirectly by using a hydraulic output to a ground based hydraulic pump/motor coupled to a rotating alternator. Both designs for the ASCS's will use technology which can reasonably be expected to be available in the late 1980's. Pioneer Engineering and Manufacturing Company of Warren, MI completed an "independent" assessment of both the MTI and STC conceptual designs. The Pioneer assessment showed that both designs are manufacturable and have the potential to easily meet DOE's cost goals. Features of the ASCS designs using a free-piston Stirling engine, a liquid metal heat transport system, a receiver and the methods of providing electricity to the utility grid will be reviewed.

A follow-on effort to complete the ASCS design, fabricate, assemble, test with delivery of a complete system to SNLA was initiated in early 1988. Involvement with manufacturers (with cost sharing) was requested to enhance the free-piston Stirling technology and subsequent commercialization of the ASCS. In early 1989 multiple contracts were awarded to Cummins Engine Co., of Columbus, IN (free-piston with linear alternator) and Stirling Technology Co. of Richland, WA (free-piston with hydraulic output) to complete the preliminary design (PD) of each ASCS. A Failure Modes and Effect Analysis (FMEA) will be used to identify critical items with their failure modes during the PD effort. One of the PD's will be selected for the final design, hardware procurement, assembly and test of the ASCS at the SNLA test facilities in Albuquerque, NM in 1991.

ADVANCED STIRLING CONVERSION SYSTEM (ASCS)

- DOE STUDIES HAVE INDICATED STIRLING ENGINES AS A LEADING HEAT ENGINE CANDIDATE FOR DISH-ELECTRIC SYSTEMS

- STIRLING ENGINES COUPLED WITH HEAT-PIPE RECEIVERS HAVE THE POTENTIAL TO MEET DOE'S LONG TERM GOALS:
    - PERFORMANCE (HIGH EFFICIENCY & POWER)
    - MANUFACTURABILITY WITH COST
    - LIFE AND RELIABILITY

- IAA WITH DOE-SNLA

- FREE-PISTON STIRLING ENGINE FOCUS OF SYSTEM DESIGNS

RKS89-001.2

ASC SYSTEM INCLUDES:

- RECEIVER
- HEAT TRANSPORT SYSTEM
- CONVERSION SYSTEM { STIRLING ENGINE; POWER OUTPUT DEVICE }
- POWER CONDITIONING AND CONTROLS
- AUXILIARIES

RKS89-001.3

ASCS DESIGN REQUIREMENTS

- POWER OUTPUT - 25 kWe
  120V, 1 PHASE, 60Hz or 240V, 3 PHASE, 60 Hz

- SYSTEM EFFICIENCY (RECEIVER INPUT TO ELECTRIC OUT) >33%

- DOE COST (1984 $) GOALS
  RECEIVER - < $40/m^2
  ENGINE/ALTERNATOR - < $300/kW
  ASCS - < $452/kWe

- DESIGN LIFE - 30 YR (60,000 HR) WITH MAJOR OVERHAUL AT 20 YRS (40,000 HR)

- CONTROLS - FULLY AUTOMATIC, UNATTENDED OPERATION

- UTILIZE EXISTING TECHNOLOGY

RKS89-001.12

HIGHLIGHTS OF ASCS CONCEPTUAL DESIGNS

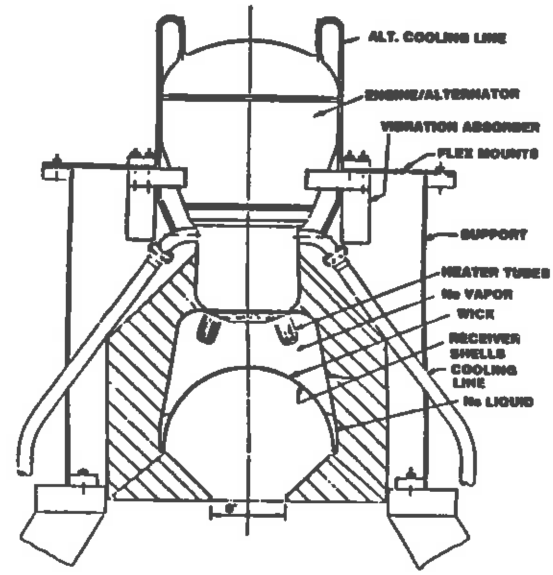
- BASE LINE CONCEPTUAL DESIGNS COMPLETED SEPT. 1987
  - MTI: HEAT PIPE RECEIVER INTEGRATED WITH A FREE-PISTON STIRLING CONVERSION SYSTEM (LINEAR ALTERNATOR).
  - STC: REFLUX BOILER RECEIVER INTEGRATED WITH A FREE-PISTON STIRLING CONVERSION SYSTEM (HYDRAULIC OUTPUT TO A ROTARY ALTERNATOR).

- PIONEER ENGR. & MFG. CO. EVALUATED THE MTI & STC CONCEPTUAL DESIGNS AND CONCLUDED BOTH ASCS'S:
  - ARE MANUFACTURABLE AND
  - CAN MEET DOE'S LONG TERM COST GOALS

RKS89-001.4

MTI'S SINGLE-PISTON STIRLING ENGINE CONFIGURATION - SEPT '87

• HEAT SUPPLIED (kWth)	75.0
• ELECT POWER (kWe)	23.2
• EFFICIENCY (SOLAR TO ELECTRIC)	30.9%
• RECEIVER/LIQUID METAL	HEAT PIPE/Na
• HEATER HEAD TEMPERATURE (K/C)	975/700
• COOLER TEMPERATURE (K/C)	333/60
• RATIO (Th/Tc)	2.9
• ENGINE FREQUENCY (Hz)	60
• WORKING FLUID	He
• PRESSURE (MPa)	10.5
• POWER OUTPUT LINEAR ALTERNATOR	240 V, 1φ, 60Hz
• ANNUAL POWER (est) (kW/hrs)	59,200
• ANNUAL EFFICIENCY	28.8%
• WEIGHT ON TBC (est) (Lbs/kG)	1500/680
• ASCS COSTS (PARETO est) ('84$)	$8429 ($363/kW)



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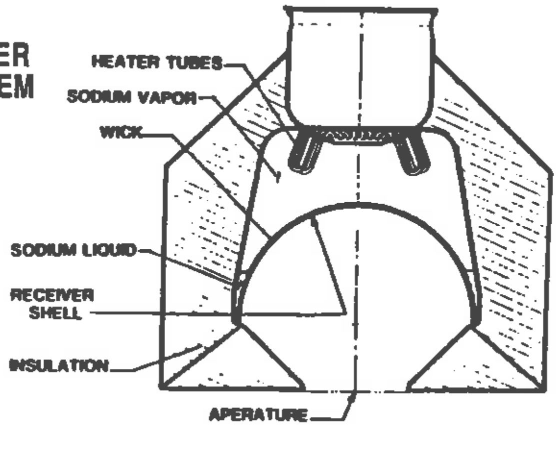
MTI HEAT PIPE RECEIVER CONCEPTUAL DESIGN

SANDERS ASSOCIATES - SOLAR RECEIVER
THERMACORE - HEAT TRANSPOR SYSTEM

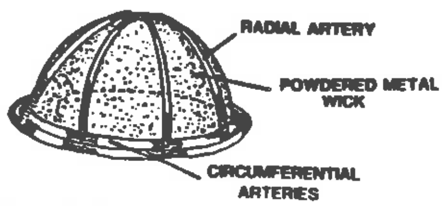
RECEIVER LOSS MECHANISMS @ 700°C

(% OF 75 kWth INPUT)

SHELL INSULATION	1.0
CAVITY RERADIATION	2.5
DISH SHADING	0.7
TRANSIENT STARTUP	0.7
CAVITY REFLECTION	2.3
CAVITY CONVECTION VERTICAL	1.0
RECEIVER NET EFF. VERTICAL	91.8%



LIQUID METAL	SODIUM
OPERATING TEMP.	700 C
ESTIMATED COST 84$	$727



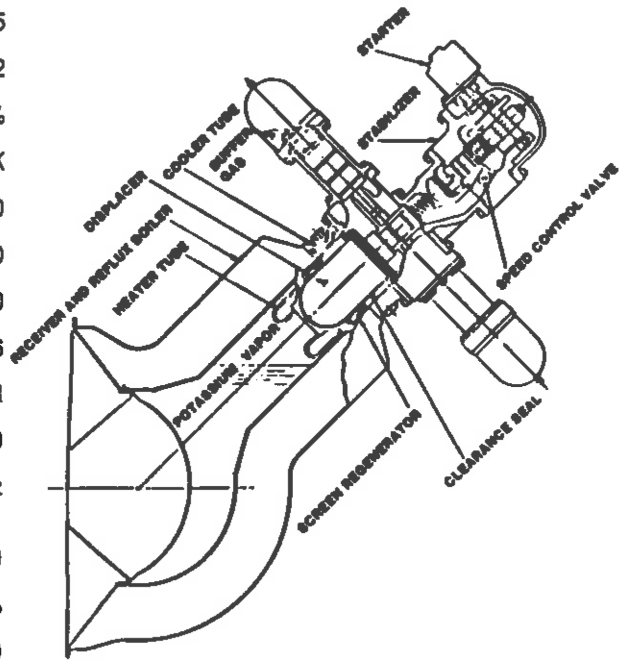
GOOD APPROACH. HOWEVER, REQUIRES DEVELOPMENT.

RKS87-001.5

STC STIRLING ENGINE WITH HYDRAULIC OUTPUT - SEPT '87

(STAND ALONE)

• HEAT SUPPLIED (kWth)	75
• ELECT POWER (kWe)	25.2
• EFFICIENCY (SOLAR TO ELECTRIC)	33.6%
• RECEIVER / LIQUID METAL	REFLUX BOILER/K
• HEATER HEAD TEMPERATURE (K/C)	973/700
• COOLER TEMPERATURE (K/C)	323/50
• RATIO (Th / Tc)	3.0
• ENGINE FREQUENCY (Hz)	46
• WORKING FLUID	He w/FREON BUFFER
• PRESSURE (MPa)	17.9
• POWER OUTPUT: HYDRAULIC PUMP WITH INDUCTION GENERATOR	240 V, 3ϕ, 60Hz
• ANNUAL POWER (est) (kW/hr)	65,200
• ANNUALIZED EFFICIENCY	31.8%
• WEIGHT ON TBC (est) (Lbs/kG)	1914/869
• ASCS COSTS (PARETO est) ('84$)	$7670 ($304/kW)



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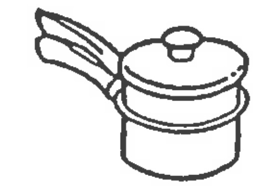
STC REFLUX BOILER RECEIVER CONCEPTUAL DESIGN



SANDERS ASSOC.-SOLAR RECEIVER
SAASKE ASSOC.-HEAT TRANSPORT SYSTEM

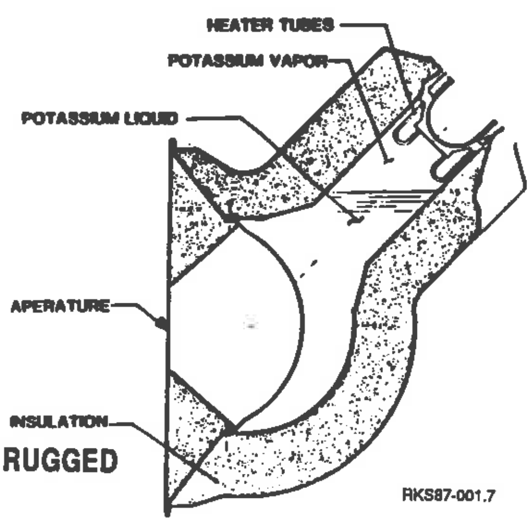
RECEIVER LOSS MECHANISMS @ 700°C

(% OF 75 kWth INPUT)

SHELL INSULATION	1.0
CAVITY RERADIATION	2.6
DISH SHADING	0.7
TRANSIENT STARTUP	2.0
CAVITY REFLECTION	2.3
CAVITY CONVECTION VERTICAL	1.0
RECEIVER NET EFF VERTICAL	90.4%

LIQUID METAL	**POTASSIUM**
OPERATING TEMP	**700 C**
ESTIMATED COST 84$	**$ 155**

SIMPLE REFLUX BOILER, INEXPENSIVE, RUGGED



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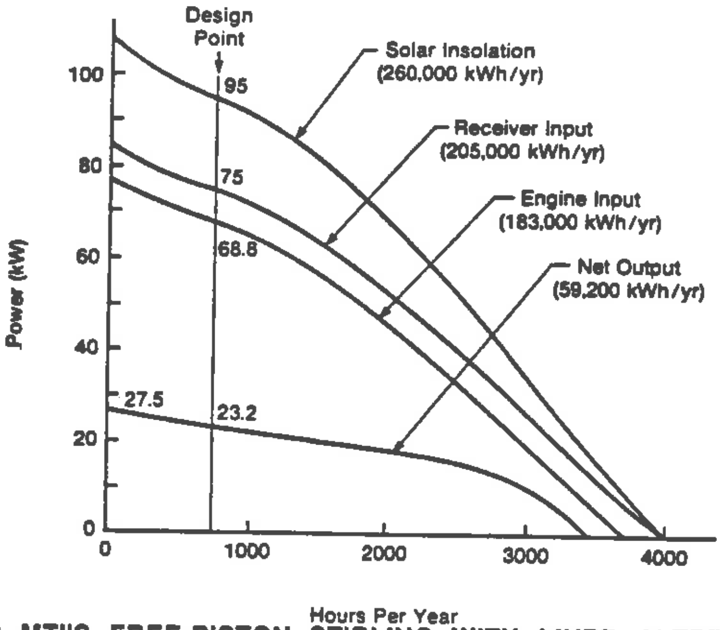
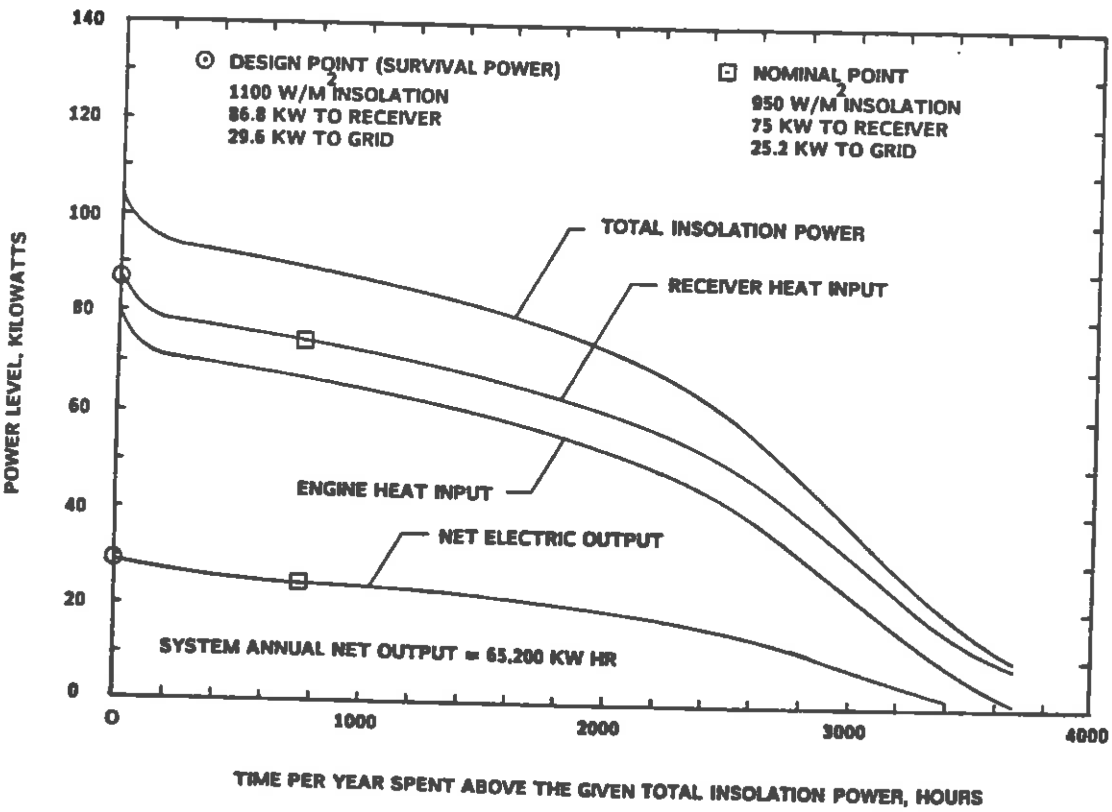
COMPARISON OF ANNUAL ASCS ENERGY PROJECTIONS



(a) MTI'S FREE-PISTON STIRLING WITH LINER ALTERNATOR

RKS89-001.14



(b) STC'S STIRLING WITH HYDRAULIC OUTPUT

RKS89-001.15

DOE COST GOALS *
(1984 $)

	CURRENT TECHNOLOGY	LONG TERM GOALS
RECEIVER	70/m²	40/m²
CONVERSION	380/kWe	300/kWe
ASCS GOALS (RECEIVER & CONVERSION)	646/kWe	452/kWe

* SOURCE: DOE/SNLA 5 YEAR PLAN

RKS87-003.36

COMPARISON OF ASCS BASELINE PROJECTED COSTS
(1984 $)

	MTI	STC
RECEIVER	727.05	155.44
STIRLING ENGINE	4843.14	3268.66
POWER GENERATION	1303.90	3323.32*
POWER CONDITIONING	541.63	——
AUXILIARIES	1013.77*	1014.25*
TOTAL	$ 8429.49	$ 7670.67
	$ 363/kW	$304/kW

* COMMERCIAL EQUIPMENT

SOURCE: FINAL PIONEER REPORT REC'D DEC. 18, 1987

RKS87-003.24
REV. JAN. 4, 88

ASCS FOLLOW-ON STATUS

- PROCUREMENT COMPLETED BY NASA LeRC FOR PRELIMINARY DESIGN, FINAL DESIGN, HARDWARE PROCUREMENT, ASSEMBLY AND TESTING OF A STAND-ALONE ASCS.

- MULTIPLE CONTRACTS AWARDED THROUGH THE PRELIMINARY DESIGN TASK. ONE FREE-PISTON STIRLING CONVERSION SYSTEM WILL BE SELECTED FOR THE OPTIONAL TASKS.

- OPTIONAL TASKS WILL INCLUDE:
  - FINAL DESIGN, FABRICATION, ASSEMBLY, C/O AND DELIVERY OF ASCS TO SANDIA.
  - FIELD SUPPORT FOR THE ASCS AT SANDIA.
  - UP TO 4 ADDITIONAL ASCSs TO BE OPERATED AND EVALUATED WITH UTILITIES.

- DESIGN FEATURES FREE-PISTON STIRLING ENGINE AND THE USE OF "EXISTING" TECHNOLOGY WITH A FOCUS ON MANUFACTURABILITY WILL BE EMPHASIZED THROUGHOUT THIS EFFORT.

RKS89-001.6

ASCS FOLLOW-ON PROGRAM

APPROACH:

- COST SHARED, COMPETITIVE PROCUREMENT
  - USE EXISTING TECHNOLOGY
  - FOCUS ON FREE-PISTON STIRLING WITH LINEAR ALTERNATOR AND HYDRAULIC DRIVE
  - UTILIZE REFLUX BOILER RECEIVER (BASELINE)
  - MULTIPLE CONTRACTS THROUGH PRELIMINARY DESIGN
- FULL SYSTEM TEST ON SANDIA CONCENTRATOR
- POSSIBLE FUTURE IN-SERVICE LIFE DEMONSTRATIONS WITH UTILITY COMPANIES OPERATING ON GRID

RKS89-001.8

ASCS PRELIMINARY DESIGN CONTRACTS

- **PARALLEL CONTRACTS AWARDED**
  - FEB'89 WITH CEC AND STC
- **CUMMINS ENGINE COMPANY (CEC), COLUMBUS, INDIANA**
  - STIRLING W/LINEAR ALTERNATOR
- **STIRLING TECHNOLOGY COMPANY (STC), RICHLAND, WASHINGTON**
  - STIRLING W/HYDRAULIC OUTPUT

ASCS CONTRACTOR TEAMS

CEC	PRIME	STC
SANDERS ASSOC.	SOLAR RECEIVER	SANDERS ASSOC.
THERMACORE	HEAT TRANSPORT SYS.	THERMACORE SAASKI ASSOC.
SUNPOWER INC.	CONVERSION SYS.	STC GEDEON ASSOC.
CEC/SUNPOWER	ANALYSIS	STC/GEDEON
McCORD	AUXS	STC
CEL	CTLS/PWR COND.	WESTINGHOUSE
CEC	FMEA	WESTINGHOUSE
CEC	MANUFACTURABILITY	WESTINGHOUSE

RKS89-001.10

ASCS FOLLOW-ON SCHEDULE