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NUCLEONICS

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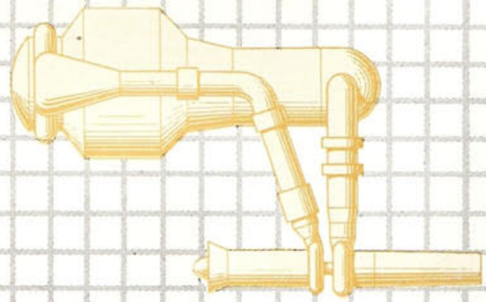
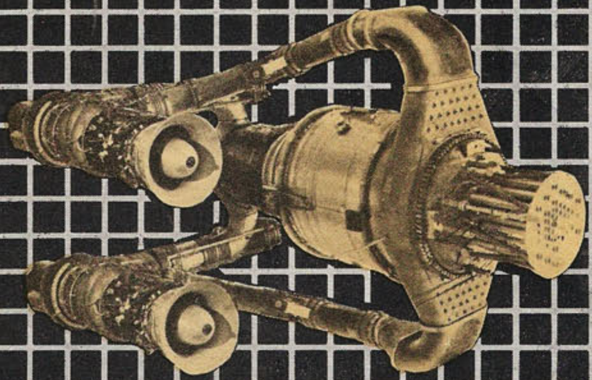


Nuclear Propulsion for Aircraft

Technical achievements of the direct-cycle program



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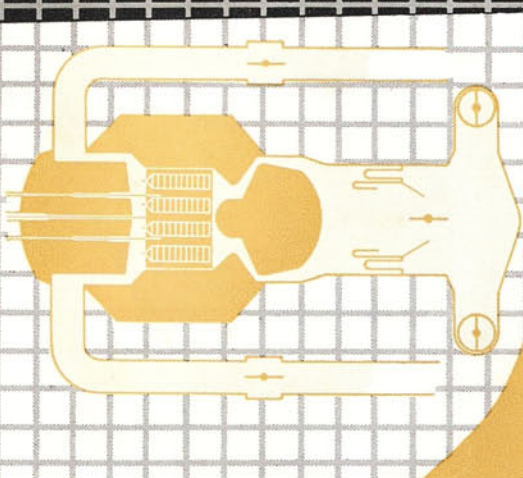

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ANP HTREs Fulfill Test Goals

By GUNNAR THORNTON and BEN BLUMBERG, *General Electric Co., Cincinnati, Ohio*

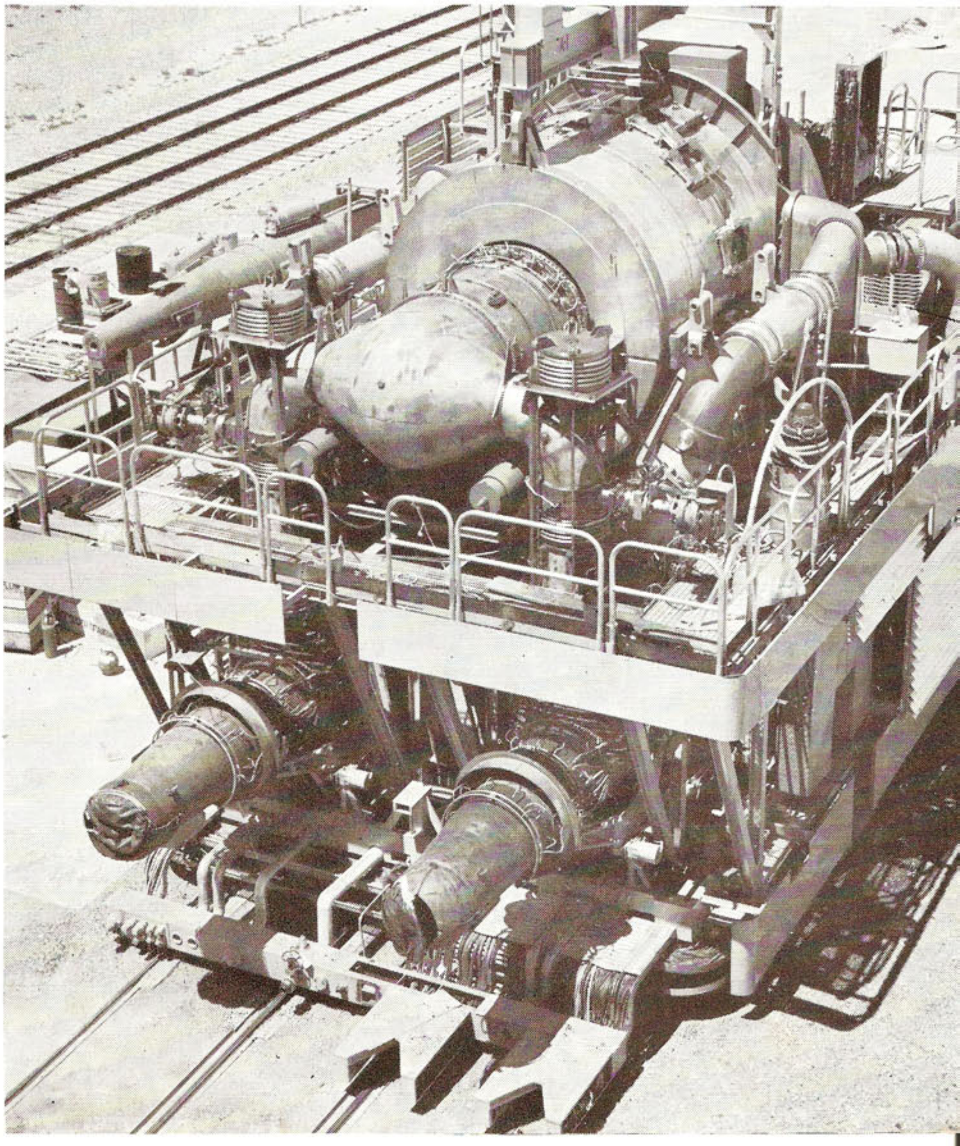
Direct-Cycle Achievements Revealed

The curtain of secrecy that has surrounded the ANP (Aircraft Nuclear Propulsion) program for over the last ten years has now been lifted far enough to disclose the technical accomplishments of one of the program's major experimental efforts—the HTRE series of tests, which have been carried out over the last five years on the air-cooled, or direct cycle, reactor concept. In summary, the tests have demonstrated through sustained power runs that a direct-cycle reactor of flyable size can operate successfully as the heat source for conventional turbojet engines. To reach this point the HTRE designers have advanced the art of gas-cooled reactor design to new levels of sophistication. As reflected in the accompanying article, their experiences with new materials, high temperatures and high performance will be of interest to many reactor designers. — **EDITORS**

PERFORMANCE results from the HTRE (Heat Transfer Reactor Experiment) series of tests at the Idaho test station have measured up to or exceeded expectations. Heavily classified until recently, the HTRE power tests have been carried out by General Electric Co. (under AEC and USAF contracts) to demonstrate feasibility of the direct-air-cycle reactor concepts it is developing for the ANP program.

The series has involved three reactor systems (HTRE-1, HTRE-2 and HTRE-3) and two reactor concepts (water-moderated and ZrH-moderated). HTRE-1 was water-moderated with its core-structure water cooled (Fig. 1). It operated a J-47 turbojet on nuclear power only (at power levels up 18.5 Mw). Compressed air from the turbojet was heated directly by Ni-Cr-UO_2 fuel elements as it passed through tubes that pierced the water moderator. HTRE-2 is merely the old HTRE-1 system mechanically modified to serve as a test facility for advanced fuel and moderator sections. HTRE-3, although it has a similar configuration (Fig. 2) and the same fuel material as HTRE-1, differs in that it has a solid moderator (hydrided zirconium) and its core structure is cooled by air. The HTRE-3 system was tested with two J-47 engines in parallel at a 32.4 Mw power level. With higher capacity engines the power levels for the two systems would be correspondingly higher. In both systems the fuel assembly consisted of nests (about 20) of concentric rings stacked in series.

HTRE-1 achieved a number of full-power runs that demonstrated conclusively the feasibility of operating a jet engine on nuclear power. HTRE-1 easily passed a 100-hr endurance test and ran with its fuel up to 1,850° F.



HTRE-3, MOST ADVANCED DIRECT CYCLE system operated to date, has powered two J-47s at 30 Mw with air heated to 1,435° F. Same core could power still larger engines

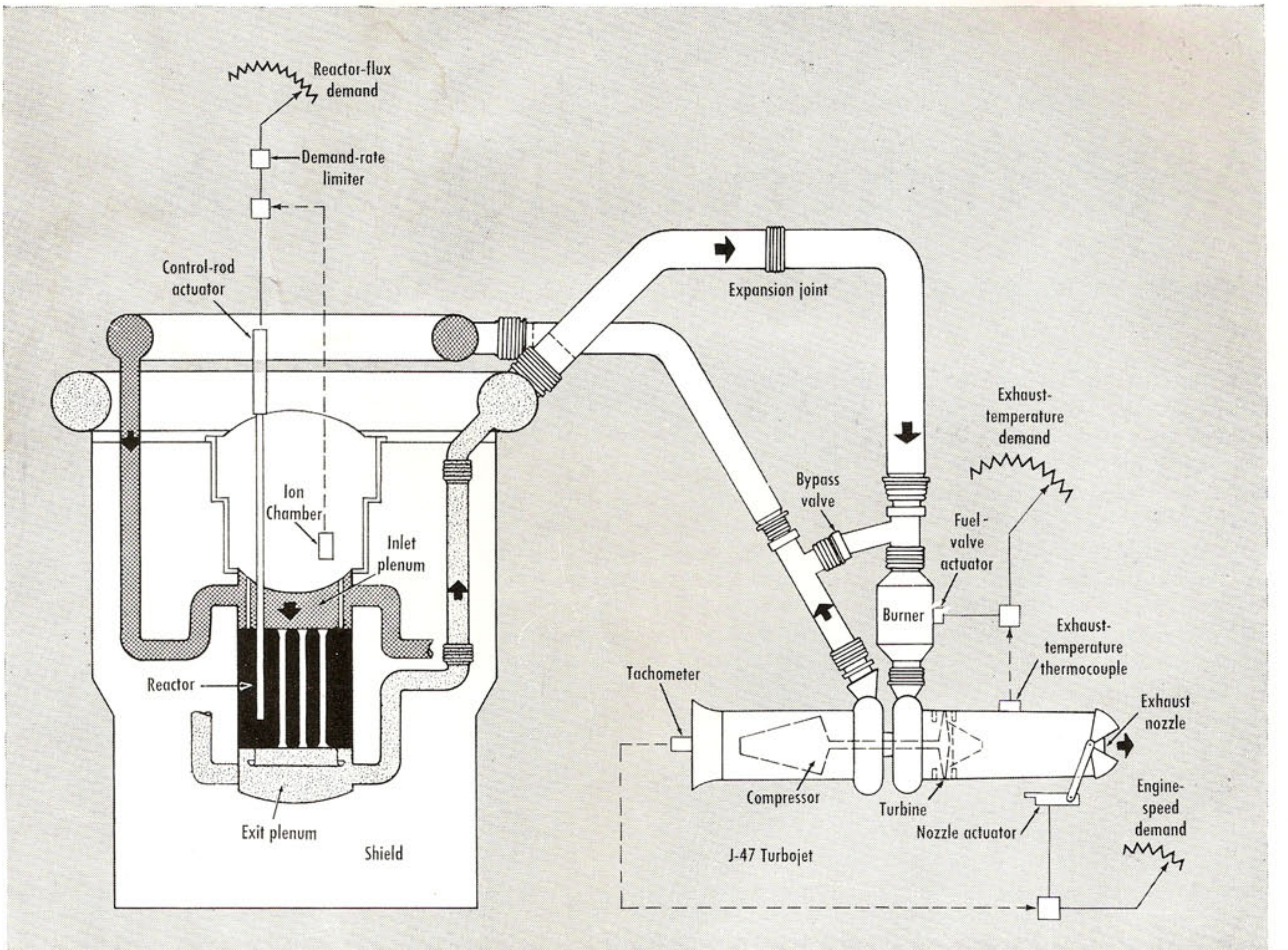


FIG. 1. HTRE-1 SCHEMATIC. In nuclear operation, air enters compressor then goes to reactor to be heated and on to turbine. Chemical burner just above turbine can also be used to heat air either in series with reactor or alone by opening core bypass

The design and testing of HTRE-3 has advanced the direct-cycle program beyond the question of feasibility to the problems of engineering optimization. While this system did not incorporate all of the design refinements now known to be practical and was primarily a "test tool," it is probably the most sophisticated gas-cooled reactor operated to date. A major accomplishment in the HTRE-3 was the demonstration that the power distribution in a reactor can be flattened to $\pm 10\%$. Designers have also accumulated valuable information on the problems of heat transfer, moderator heating, shield heating, core pressure drop, core lifetime and control. It now appears possible and practical with the technology in hand to build a flyable reactor of the same materials as HTRE-3 and similar in physical size.

With the successful achievement of its test objectives, HTRE-3 is currently taking turns with HTRE-2 (ex-HTRE-1) in further test operations at NRTS.

Although both the HTRE-1 and HTRE-3 systems have reactor cores of about the size needed to fit into an airplane, neither was intended to be the prototype of a flight system. The HTRE-1 reactor was simply suspended vertically in a large shield tank, with no attempt to simulate flight geometry in the shield, support structure, or the ducting systems. The HTRE-3 arrangement, as Fig. 2 shows, more nearly approximates a flyable configuration. In both systems air enters the compressor section of the turbojet engine(s) (HTRE-1 had one J47 turbojet, HTRE-3 has two) and then was ducted to the reactor core. The air passes directly through the reactor core and on to a chemical combustor (in HTRE-1 the air could bypass the core to the combustor through a parallel bypass duct). From the combustor, ducts carry the air back to the turbine section of the turbojet engine(s) and finally to an exhaust stack. The chemical combustor in series with the reactor allows the system to operate at a given power level with the fractional contribution of nuclear power variable between 0 and 100%.

HTRE-3 Design and Operation

The reactor in HTRE-3 operates in a horizontal position with its components supported at each end by Inconel-X tube sheets. The beryllium reflector is made of six equal segments that form a circular container for the active core. The active core contains150 moderator-fuel units. The moderator is a hydrided zirconium tube with a cross section hexagonal on the outside and circular on the inside (see Fig. 3). An insulation liner between the fuel cartridge and the moderator isolates the fuel elements from the moderator. Both moderator tubes and fuel cartridges are attached to the front tube sheet by remotely operable disconnects and freely supported by the rear tube sheet to allow freedom for thermal expansion.

The active core is 30 in. long and 51 in. in diameter. The core was

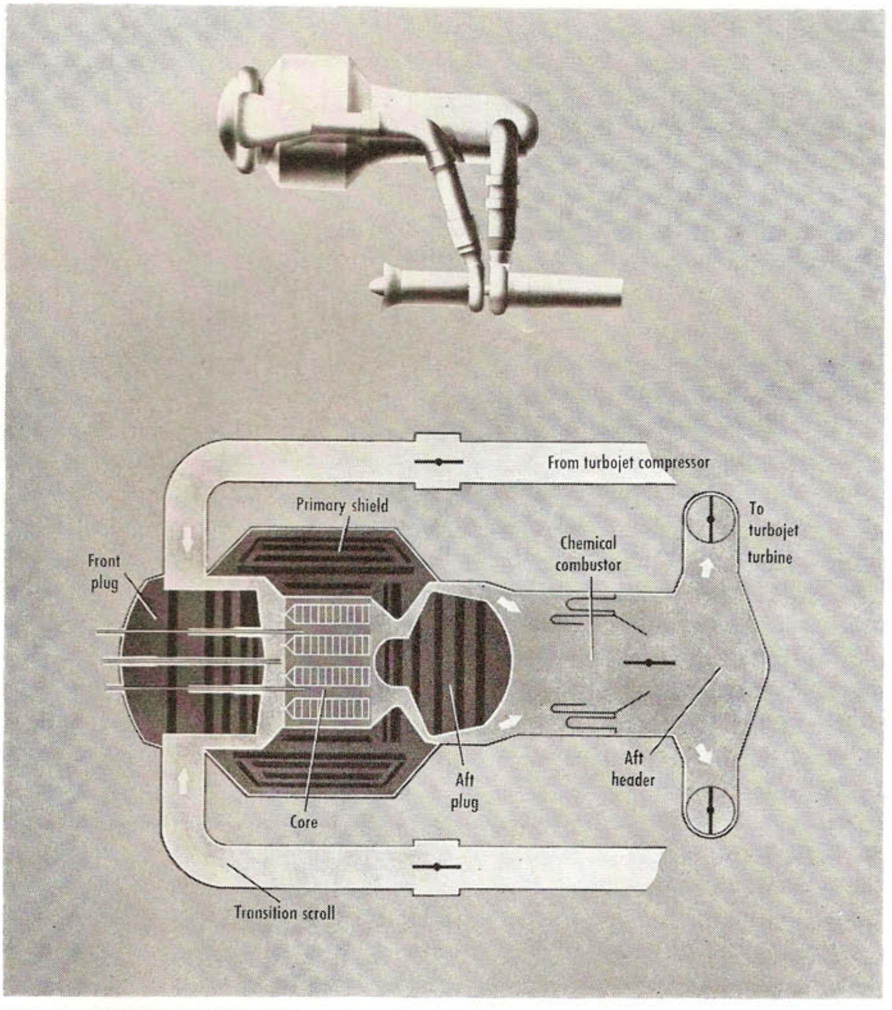


FIG. 2. HTRE-3 SCHEMATIC. More "flyable" than HTRE-1 configuration, system has reactor and chemical combustor joined together in single unit to power two J-47 turbojets

designed to take on air flow up to 850 lb/sec.

It could, therefore, easily handle the combined flow from the two J47 jets of 123 lb/sec to develop a total power of 32.4 Mw. (Were the HTRE-3 core coupled to an engine system that could take fuller advantage of its flow capacity, it could operate at a correspondingly higher power level.)

The reactor is controlled by control rods located at the junction of three moderator cells; the rod inventory includes 30 shim rods, 3 dynamic rods for power changes and 15 safety rods normally out of the core except for shutdown. The arrangement of the control rods and the core's cross section is shown in Figure 3.

The shielding, shown in Fig. 4 is of lead and water. The shields are cooled by circulating the water between the lead slabs and rejecting the heat to a water-to-water heat exchanger on the dolly. The Inconel-X pressure vessel supports the reactor, front plug and rear plug and radial shield.

The beryllium-reflector sectors are composed of hexagonal blocks with longitudinal holes for cooling. With insulation separating the reflector from the active core, the reflector operates at temperatures up to 1,200° F.

Air also cools the moderator tubes through longitudinal slots cut out from the inside diameter. The moderator has operated at temperatures up to 1,300° F for 100 hours without excessive oxidation or hydrogen loss. To accomplish the gross radial power flattening the hydrogen content of the hydrided zirconium moderator tube was varied from tube to tube in the fabrication process.

The control rods are made up of short segments of clad europium oxide held together by straps. This articulated design allows the rod to deflect as required while traversing its guide tube. These rods have operated satisfactorily at temperatures up to 1,600° F in passages offset from the actuator axis by 0.180 in. The rods, with a rate of travel of 5 feet per second and length stroke of 20 inches, have survived 34,000 cycles under varying conditions without failure or malfunction.

The fuel elements are UO_2 in a matrix of 80% Ni-20% Cr and clad with 80% Ni-20% Cr stabilized with niobium. The specific design of the fuel elements is still classified. The fuel elements have operated satisfactorily at temperatures up to 1,900° F for periods in excess of 100 hours.

An automatic system controls neutron flux level from 10^{-4}% to 100% full power, with the 10 to 100% range controlled to ±1% full power. A second system automatically controls temperatures from 1,000° F to 1,600° F ±10° F. The engine speed is automatically controlled by varying the exhaust nozzles to maintain the two turbojet engines at constant conditions while operating with the common heat source.

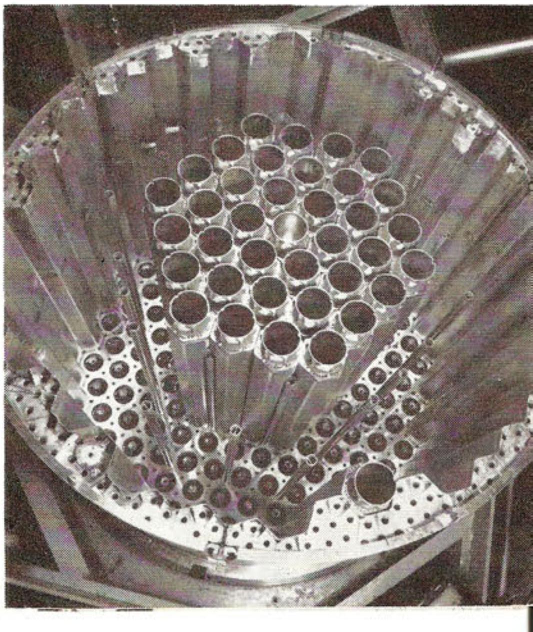
Except for a brief excursion due to nuclear-sensor saturation at the beginning of testing* the reactor performed as predicted throughout the operation of the tests. These tests consisted of a total of 4,935 Mwh with 126 hours at design power (32 Mw). From all indications to date, the remaining core life is several times this amount. A summary of the performance data is given in Table 1.

Design Optimization

Since power output is limited by the maximum permissible temperature of

* Reported in NU Jan. '59, p. 24; GE-ANP will soon release a more complete report on this incident.

FIG. 3. HTRE-3 CORE view shows basic core unit composed of air flow tube surrounded by hexagonal zirconium-hydride moderator. Each tube receives a single fuel cartridge. Small tubes standing alone are control rod guides



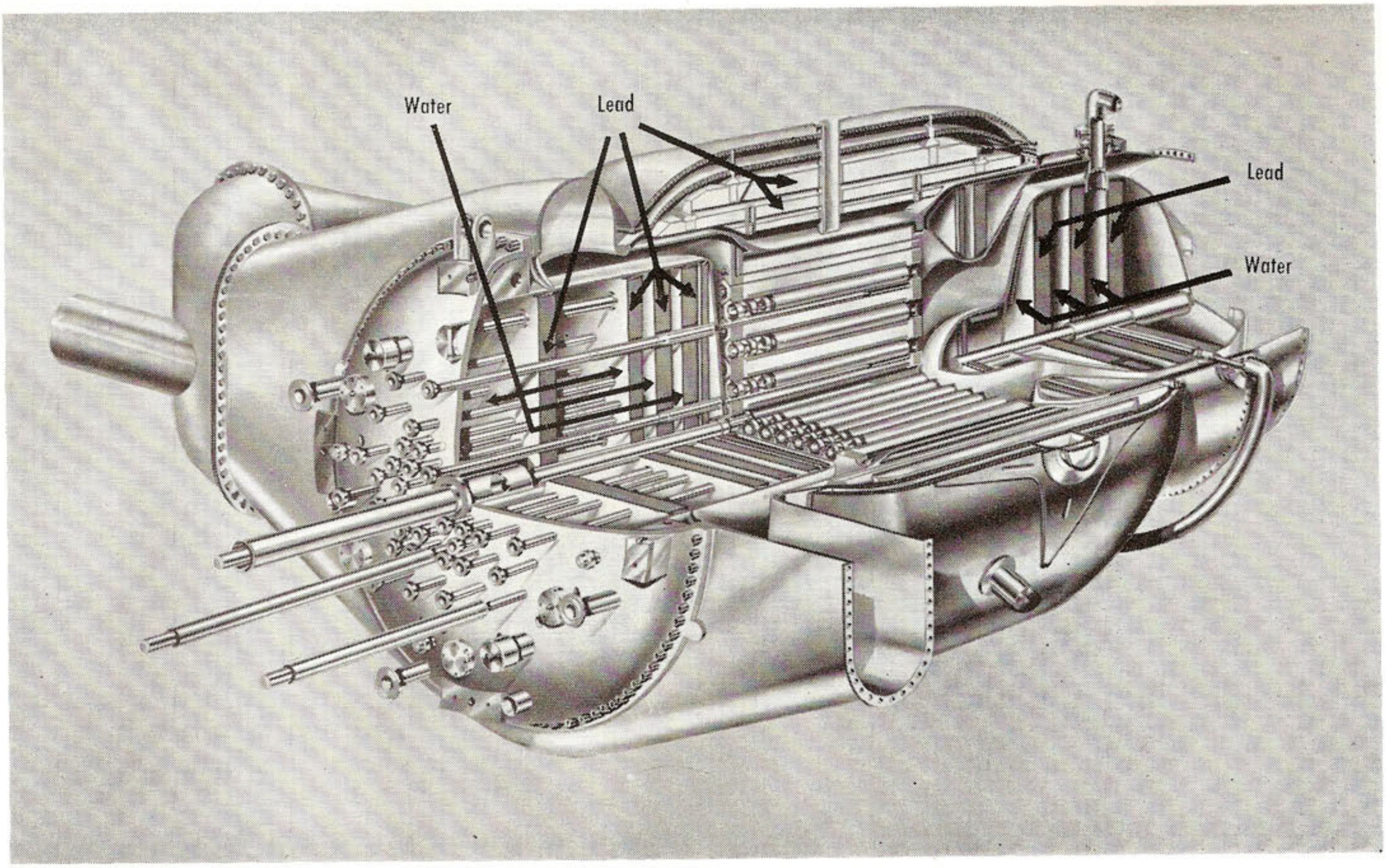


FIG. 4. ARTIST'S CUTAWAY shows lead and water shielding arrangement around HTRE-3 core

the fuel element, over-all power output is increased by making the radial power distribution as uniform as possible throughout the core and adjusting the longitudinal power. This was done in the HTRE-3 by varying the moderator hydrogen content for gross radial control, shimming the fuel elements with boron steel for circumferential power control, extending the moderator beyond the active core for longitudinal power control, and varying fuel loading in individual fuel elements for fine radial power control. While the power distribution in HTRE-3 was adjusted and extensively measured, its control was limited by some features of the design and the time available to modify the design. The goals for this core were merely to demonstrate power-flattening capabilities and to obtain data for making performance predictions.

TABLE 1—HTRE-3 Performance Data

	Design conditions	
Reactor power to air (Mw)	32.4	
Reactor air flow (lbs/sec)	123	
Turbine inlet air temperature (°F)	1,330	
Compressor discharge temperature (°F)	385	
Compressor discharge pressure (psia)	53.5	
	Predicted	*Measured*
Max. fuel element temperature (°F)	1,880	1,900
Max. moderator temperature (°F)	1,175	1,120
Max. reflector temperature (°F)	1,100	1,030
Max. temperature, discharge air from fuel (°F)	1,640	1,640
Average temperature, discharge air from fuel (°F)	1,430	1,435
Average temperature, discharge air from moderator (°F)	968	880
Average temperature, discharge air from reflector (°F)	955	940
Average temperature, discharge air from control rods (°F)	805	480
Reactor pressure drop (psi)	6.05	6.2
Pressure drop, compressor to turbine (psi)	10.8	9.3

A temperature survey of the core indicated the maximum air temperature rise through the fuel elements exceeded the average by 17% which corresponds to a peak power sector of 14% greater than the average. Part of this variation is attributed to: (a) intentionally reduced power at the outside of the fuel cartridge because of space variations between the cartridge and the insulation liner, and (b) lower than average power in the center of the cartridge because of manufacturing limitations at that time.

These problems were recognized and subsequent designs offer corrections. Because of these problems a more indicative picture of the core power flattening can be obtained from the maximum power area in the fuel elements, i.e., the area between the inner and outer low power sections. The measured peak temperature rise with one exception did not vary from the average by more than $\pm 8\%$. The one exception was 12% and this was attributed to the fuel-cartridge and insulation-liner tolerance problem.

TABLE 2—HTRE-1, Design, Mechanical, Nuclear and Thermodynamic Data

MECHANICAL DATA

Over-all Reactor Dimensions	
Over-all reactor length (in.)	55.25
Over-all reactor diameter (in.)	59
Number of air passage tubes	37
Tube outside diameter (in.)	4
Tube-wall thickness (in.)	0.080
Fuel Elements	
Active length (in.)	29.13
Outside diameter (in.)	3.432 ± 0.015
Material of meat	UO_2 (93.4% enriched) and modified 80% Ni-20% Cr
Cladding material	Modified 80% Ni-20% Cr
Reflector	
Side reflector	4 in. Be; 12 in. wtr
Dimension across flats, inside (in.)	30.758
End	12.5 in. water-Al matrix
Fuel tube insulation	
Material	Thermoflex RF-1200
Thickness (compressed) (in.)	0.1
Cover material	310 stainless steel

THERMODYNAMIC DATA

Reactor	
Core inlet air temperature (°F)	359
Core inlet pressure (psia)	54.95
Core exit temperature (mean) (°F)	1,335
Core exit pressure (psia)	47.54
Mass velocity in fuel elements (lb/ft²/sec)	
Core inlet	26.72
Core exit	27.3
Maximum fuel element operating temperature (°F)	1,700 (average)
Total heat transfer area (ft²)	1,194
Reactor power-to-air (Mw)	15.9
Reactor power-to-water (Mw)	1.6
Total reactor power (Mw)	17.5
Engine	
Compressor pressure ratio	4.95
Altitude at NRTS (ft)	5,000
Air weight flow (lb/sec)	59.5
Compressor discharge temperature (°F)	393
Turbine inlet temperature (°F)	1,295

NUCLEAR DATA

Uranium inventory (lb)	90 (93.4% enriched)
Burnup (lb)	0.2
Expected cold, clean excess in HTRE ($\%\Delta k/k'$)	3.6
Moderator temperature coefficient ($\%\Delta k/k/°F$)	0.012 (at 140 °F)
Thermal fission-fraction	0.61
Leakage fraction	0.29
Total control-rod value ($\%\Delta k/k$)	9.09 (24 rods)
Total shim-scram value ($\%\Delta k/k$)	7.77 (21 rods)

REACTOR COMPOSITION

Active Core Dimensions	
Diameter across flats (in.)	30.758
Diameter across corners (in.)	35.516
Volume (ft³)	13.809
Active Core Volume Fractions	
Water	0.402
Aluminum and insulation	0.0531
80% Ni-20% Cr	0.0576
Uranium (93.4% enriched)	0.00588
Stainless steel	0.000942

In this type of reactor we can define the ratio of the temperature rise from the inlet air to the fuel element surface (ΔT_T) and the air temperature rise through that section of the fuel element (ΔT_b). This ratio $\Delta T_T/\Delta T_b$ is very nearly a constant provided the power distribution in the core does not change. For the HTRE-3 this ratio was found to be 1.23. This ratio could be improved by shifting the power in the fuel element toward the air-inlet end of the reactor (through an increase in the fuel loading in this section) and by increasing the heat transfer area in the downstream stages. While this adjustment was not optimized in the HTRE-3 it was in subsequent designs to give a ratio of 1.17.

These adjustments, however, are not accomplished without paying a price in core pressure drop, which ranks in importance with the turbine-inlet temperature. In the HTRE-3 the methods of predicting pressure drop were verified and subsequent developments in fuel element design have reduced the pressure drop. This reduction provides a greater freedom in optimizing the heat transfer characteristics.

The so-called cooling penalty for the moderator, reflector, control rods and core structure can be easily evaluated by taking the average air temperature rise through the fuel elements and dividing this by the temperature rise through the entire core. These values are found from the performance summary above and give:

$$\Delta T_{\text{Fuel}}/\Delta T_c - \frac{1435 - 385}{1330 - 385} = 1.11$$

For the HTRE-3 this shows that cooling (other than the fuel elements) costs approximately 105° F in turbine-inlet temperature. However, the moderator in the HTRE-3, which is the major extra cooling item, was operating considerably below the design value. In addition the moderator volume fraction in the HTRE-3 was 34%, which is greater than required. If this is reduced (by increasing fuel loading or the hydrogen content of the moderator), the cooling flow would be reduced approximately in direct proportion.

While the absolute performance of this system was limited by a not too optimum design, the data obtained show that a higher performance system can be produced with the technology now available. The following is a simplified extrapolation from the HTRE-3 data to such a system.

Consider the following relationships:

	HTRE-3	*Modified Design*
$\Delta T_b'/\Delta T_b$	1.17	1.10
$\Delta T_b/\Delta T_c$	1.11	1.09 for $T_c = 1550$ 1.11 for $T_c = 1650$
$\Delta T_T'/\Delta T_b'$	1.23	1.17

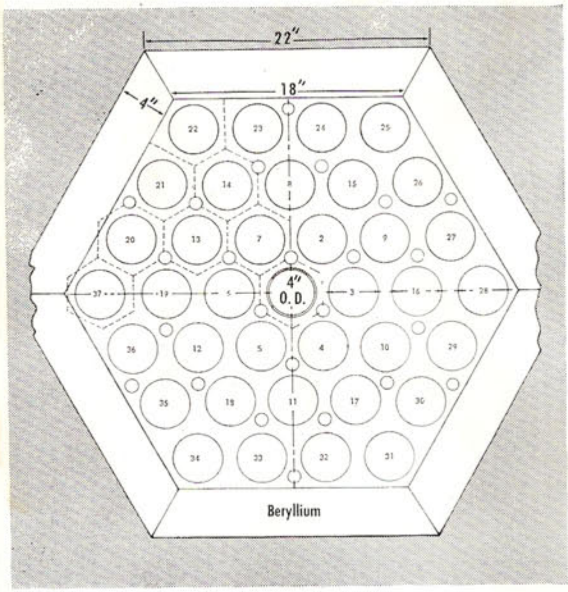


FIG. 5. HTRE-1 CORE arrangement involves six unique cell configurations e.g. cells 1, 7, 23, 14, 21 and 22

Here the *primes* refer to peak temperature.

- $\Delta T_b'/\Delta T_b$ is basically a peak to average power ratio in the fuel elements.
- $\Delta T_b/\Delta T_c$ is the penalty for core components other than the fuel elements.
- $\Delta T_T'/\Delta T_b'$ depends on the heat transfer characteristics of the system.

In terms of these ratios the maximum fuel element is

$$T_s' = \Delta T_c \left(\frac{\Delta T_b \, \Delta T_b' \, \Delta T_T'}{\Delta T_c \, \Delta T_b \;\; \Delta T_b'}\right) + T_1$$

Figure 6 shows a plot of this equation for the improved reactor design. The modified design assumes a core inlet temperature $T_1 = 700°$ F and an increase in the moderator temperature to an average of 1,150° F and a reduction in the moderator volume fraction from 34% to 24%.

With the materials used in the HTRE-3, this design could then have an exit air temperature of 1,500–1,650° F. The exact air temperature would depend on the operating time desired—1,000 hr for 1,500° F and 25 hr for 1,650° F.

In summary the performance of the HTRE-3 has demonstrated that a system using the same materials can be designed which would power a modern gas-turbine power plant. The reactor would have a size, pressure drop and power capability compatible with flight requirements. Advanced materials will extend this performance but flight is possible and practical with the technology now in hand.

HTRE-1 Description

In the HTRE-1 reactor unpressurized water at 160° served as both moderator and structural coolant. The reactor structure was fabricated of aluminum and consisted of a cylindrical water vessel penetrated by 37 four-in. dia tubes in a hexagonal pattern with radially varying spacing. The reactor air flowed through three tubes each of which contained a fuel cartridge. The tubes were lined on the inner surface with a thin sleeve of stainless-steel-jacketed, mineral-wool felt insulation to reduce heat flow into the water moderator.

Tube sheets at each end of its tube bank joined with a cylindrical shell to form a water-tight tank 59 in. in dia and 55 in. long. This reactor tank also contained the reflector—beryllium slabs four inches thick, spaced ⅝ inches from the outside tubes and supported from brackets welded to the tube sheets. The control rod guide tubes, welded into the top tube sheet, performed double duty as inlet tubes for moderator water. The water moderator filled the entire reactor vessel except the air passages. After picking up heat from the beryllium reflector and aluminum structure, the water circulated to an external radiator.

The fuel cartridges were made of an 80% Ni-20% Cr alloy impregnated with UO_2. Each fuel cartridge had a loaded length of 29.125 in. The unloaded air tube and water matrix extended beyond each end of the active core to serve as the end reflector. The core volume fractions shown in Table 2 were computed for a total core volume defined by the inside surface of the beryllium reflector.

The gross radial power was equalized from tube to tube by varying the spacing of the tubes. Figure 5 shows the six unique cell configurations (e. g. tubes 1, 2, 9, 15, 25, 26) that defined the core geometry. Near the outside of the reactor, where the power would normally be low, the tube spacing was increased. Thus more moderator was associated with each tube and the thermal flux between tubes was made equal. The beryllium reflector was also important in maintaining a sufficiently high flux in the outer tubes. An important feature of this method of power flattening is that all fuel cartridges can be identical, making for simple fabrication.

The fine radial power distribution was flattened within a fuel cartridge by radial variation in the fuel loading within the cartridge. Since the fuel loading was uniform in its longitudinal direction, the reactor had the conventional longitudinal "cosine" power distribution.

The basic scheme of controlling the HTRE-1 power system was similar to that of HTRE-3. The power system was started on chemical fuel alone with compressor air passing through the cold reactor. Then, the reactor was started and nuclear power was increased. When the nuclear heat added to the air detected as an increase in air temperature by the turbine exhaust thermocouple, the chemical fuel valve would start to close in an attempt to maintain the exhaust temperature at the predetermined level. As the reactor power was further increased, the chemical fuel would shut off completely so that operation was completely on nuclear power.

HTRE-1 Operation

During its life time HTRE-1 underwent three series of power tests (designated IET #3, #4, and #6) at its Idaho Test Station starting December 27, 1955 and ending January 3, 1957.

IET #3. The first series of operational tests succeeded in operating exclusively on reactor energy at power levels from ~0 to 16.9 megawatts. After about 6 hours of accumulated operation at full nuclear power, the reactor was returned to the hot shop, to check the possibility of fuel element damage as indicated by the exit air-radioactivity monitors. Examination of the fuel cartridges revealed that several cartridges were damaged, with segments of the fuel elements partially melted or oxidized. The damage resulted from differential air pressure across the insulation sleeve between the fuel cartridge and the wall of the air tube. The pressure differential had caused the insulation sleeve to collapse against the fuel cartridge restricting airflow and preventing adequate cooling of the outer fuel surface.

Except for the insulation liners, system components generally performed in good to excellent agreement with design predictions. The observed distribution of fuel element temperatures and the maximum value of selected fuel element temperatures were greater than anticipated, due apparently to high temperatures near the damaged regions.

The reactor core was reassembled with 24 of the original fuel cartridges and a new set of insulation liners partially redesigned to provide pressure relief.

IET #4. The second series of power tests (IET #4) with the modified insulation liners showed no significant deviations from the results of the first tests. The system was again shut down for disassembly and inspection in the hot shop—this time to determine whether any further design modifications were necessary for the final endurance run. The test operation and post-examination indicated that the insulation sleeve redesign was not completely successful in that damage had still occurred to one fuel cartridge.

During the IET #4 series, the reactor operated a total of 1,877 megawatt-hours at a maximum sustained power level of 16.0 megawatts-to-air. Partial chemical heat was supplied during the entire IET #4 operation. The maximum core discharge temperature was 1,394° F. The total operating time at a power-to-air of 16 megawatts was 84 hours.

IET #6. The last power series (IET #6) used redesigned and reinforced insulation liners together with a complete set of virgin fuel elements. In low power tests, at the start of the series, it was found possible to operate the reactor with a temperature-rise across the core three times the inlet temperature; there were no indications of the flow maldistribution or instability that had been considered possible for this low-flow condition.

A two-phase all-nuclear endurance testing program was formulated for IET #6. In phase A the reactor was required to demonstrate 100 hours of engine operation on full nuclear power at a core discharge temperature of 1,280° F and thus meet the primary endurance demonstration objective. This the reactor accomplished without incident. For Phase B, the reactor exit-air temperature was raised to 1,380° F, which corresponds to a maximum fuel element temperature of 1,850° F, and was 150° F in excess of the design point. After 39 hours at these conditions the system was returned to the hot shop for examination.

Post-operation observation of the fuel element indicated no gross oxidation or melting as observed during previous operations, indicating that the insulation liner redesign was successful.

HTRE-2 Facility

HTRE-2, the second designation of the experimental series, is the name that was bestowed upon HTRE-1 after the reactor was modified to accomodate special test specimens of more advanced fuel element and moderator assemblies. The facility has made possible tests that could not be performed in ordinary in-pile experiments. In HTRE-2 the core was the same as it had been in HTRE-1 except that the central seven air tubes were removed and replaced by a hexagonal void (see Fig. 7). Sections of advanced reactors were inserted into the "parent core" through an opening in the top shield plug and were cooled by air drawn from the common plenum chamber above the reactor.

After HTRE-2 accumulated 552 hours at test power levels, 20 of the 25 fuel cartridges were replaced in the parent core to restore the margin of reactivity. The fuel elements themselves appeared to be metallurgically and mechanically in good condition and capable of operation for an indefinitely longer period if reinstalled into a reactor of greater excess reactivity margin.

In summary, the HTRE-2 parent core has operated for an accumulated total of 992 hours with fuel element temperature between 1,200 and 1,750° F and reactor exit air temperature between 875° F and 1,125° F. Five of the fuel cartridges have served for the entire 992 hours with no external manifestation of metallurgical or mechanical difficulties.

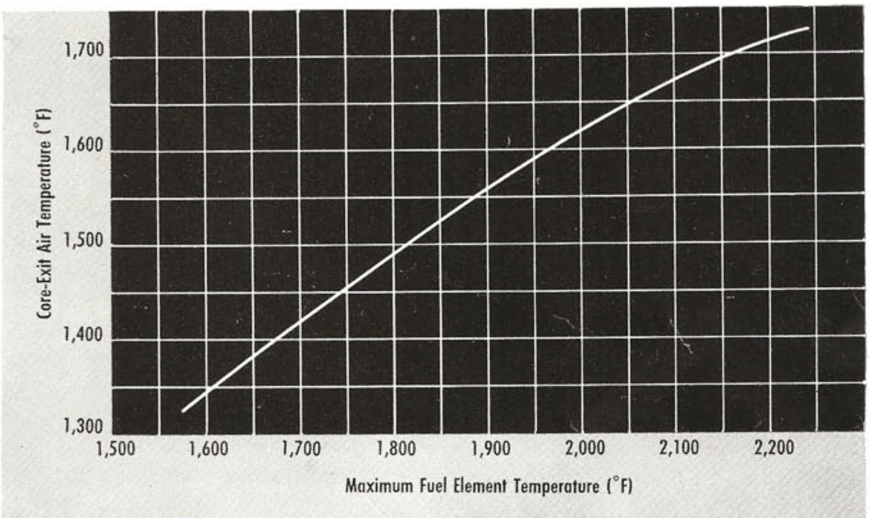


FIG. 6. AIR TEMPERATURE at core exit vs. maximum fuel surface temperature in core for optimized design extrapolated from HTRE-3 data. Air-inlet temperature = 700° F

FIG. 7. HTRE-2 used to test advanced reactor components in central void shown in core was built from old HTRE-1 after it had finished test series