N92-11095

PARTICLE BED REACTOR
NUCLEAR ROCKET CONCEPT

Hans Ludewig
Brookhaven National Laboratory

It is gratifying to see that we are not the only ones talking about the particle bed reactor anymore (Refer to concept just presented by J. Ramsthaler).

The concept (see Figure 1) consists of fuel particles, in this case (U,Zr)C with an outer coat of zirconium carbide. These particles are packed in an annular bed surrounded by two frits (porous tubes) forming a fuel element; the outer one being a cold frit, the inner one being a hot frit. The fuel elements are cooled by hydrogen passing in through the moderator. These elements are assembled in a reactor assembly in a hexagonal pattern. The reactor can be either reflected or not, depending on the design, and either 19 or 37 elements, are used. Propellant enters in the top, passes through the moderator fuel element and out through the nozzle.

Beryllium is used for the moderator in this particular design to withstand the high radiation exposure implied by the long run times.

As far as design philosophy is concerned, I would like to introduce another parameter (Figure 2). Stan Gunn talked about the importance of specific impulse. I would like to talk about the added importance of thrust-to-weight ratio as well. Mission analyses indicate that the thrust-to-weight ration should be above 4.0.

We looked at two reactor designs; one that tried to maximize the thrust-to-weight and one tried to maximize the specific impulse (Figure 3). To maximize the thrust-to-weight requires a high power density, high pressure, and high temperature. These requirements result in a small, high thrust reactor.

The high specific impulse design operates at reduced pressure to introduce some dissociation of the hydrogen and thus increase the specific impulse. A low power density is implied by operating at a low pressure. Because of the lower density of the gas, the engine becomes bigger, heavier, and the thrust is lower.

These are the parameters which were considered (See Figure 3). The engines range from 1,000 megawatts to 5,000 megawatts, in the high thrust-to-weight cases and 500 to 2,000 megawatts in the specific impulse case.

Power densities in the bed were also varied. This is not average power density of the core, but in the bed. The chamber temperatures range over 2,500K to 3,500 K and in the low pressure case we increased the temperature beyond from 3,000 K to 3,750 K.

The pressures range considered was 7 MPa - 14 MPa, depending on power density. At the higher bed power density, higher pressures are required. The low pressure case operated at a much lower pressure; 0.5 MPA.

We did full up analyses of these cores. These reactors were all found to be critical and coolable. We took into account pressure drops and heat transfer in the fluid dynamics analyses.

An important point I want to make here is that thrust to weight ratio drops (Figure 4) when comparing the two reactor design philosophies. These are unshielded and still within the limits of the baseline. However, as soon as one adds on a shield, and again this shield is a fairly cavalier design, one notices that the low pressure design drops way down and is below the baseline requirement.

Technology status (see Figure 5) is divided into analysis, proof of principle experiments and prototype experiments. As far as analysis is concerned, we use the Monte Carlo code (MCNP) that is standard in the industry.

In the case of fluid dynamics, we did have to generate our own codes. One cannot use an off-the-shelf fluid dynamics code and modify it. We made a 1-D survey code and transient code to study start-up. These were reported on at the Albuquerque meetings in 1987.
We use the standard Ergun correlation for pressure drop in the bed. There has been additional work by Achenbach that essentially confirms this work and that was reported in 1982 in Munich.

As far as the materials work is concerned, we have done various tests and the most significant had to do with the compatibility of zirconium carbides and hydrogen. Again, this was reported in 1985 in Albuquerque.

As far as the electrically heated tests are concerned, we built full diameter, half length fuel elements, and demonstrated that we can extract ten megawatts per liter from the bed.

In the case of fuel development, many people have looked at zirconium carbide coated fuel particles. I just refered to an ORNL report here, but work has gone on in this country. The Germans have looked at it, and so have the Soviets and Japanese. As for the UC/ZrC kernel, there is a reference that goes back to 1963 that reported manufacturing these. So I would put the technology readiness of this concept at around four.

The other item we were asked to address was the potential for new technology and safety requirements (see Figure 6). I think that for our concept, coatings are important. The mixed carbide coatings which have a melting point of about 4,000 K would really

help.

Finally, enhanced light weight structures are important. Particularly if one can make them out of low Z materials in an effort to reduce the radiation heating, particularly if high power densities are required to maximize the thrust-to-weight. The platelet technology which Aerojet worked on for some time for reentry vehicles would be very useful in our moderators.

Safety issues are generic for most concepts (see Figure 7). Fuel element test reactor safety is uppermost in our work. The ETR (Element Test Reactor) will be used to develop the fuel element for the full scale reactor.

Ground test facilities are required to test several engines, to develop a reliable system. I would like to see a space craft with at least three engines on it, and that's where the high thrust-to-weight ratio requirements comes in. If one can design an engine that has a high thrust-to-weight ratio, one can afford to put several of them on the vehicle and still meet the thrust-to-weight goal.

Launch criticality and Earth reentry; these are standard accident scenarios that we all have to analyze.

Several energy release scenarios exist. Those associated with hydrogen deflagrations/detonations will probably be more important than those from nuclear events. I think we all know what is required there.

We think that we can propose multiple engines with our concept (see Figure 8). If we select a high thrust-to-weight ratio, small shields are implied. These would be smaller since they don't have to be shadow shields and they would also be easier to decouple, assuming that's a requirement.

The fuel particles are small and most particles in the bed are relatively cool. The only ones that are hot are the ones that are closest to the hot frit. Three-quarters of them will be cooler and thus failure and fission product release is expected to be low.

We have tried to make our designs using light weight materials with low Z to reduce the radiation heating effects. The thermal gradients are fairly moderate across most components, implying low thermal stress.

As far as key technology issues are concerned for high temperature particles, the erosion resistance is certainly important (see Figure 9). I would like to point out at this stage that the velocity of the coolant through the bed is of the order of 50 to 100 meters per second. Tests should be done on particles in hydrogen at about 7 MPa, at operating temperatures of about 3,000 K at that velocity.

Again, the same comments hold for the frit. The velocities are again the same since the coolant flows radially through the frit. The cold frit has to be manufactured, as was pointed out earlier, to have variable porosity to shape the flow.

We have a large selection of moderators at our disposal. In the current design, we use beryllium. However, various materials can be used, since the moderator operates at inlet temperature. Thus, we can use it to maximize whatever parameter we want to maximize.

It is important to carry out an integrated element test (see Figure 10). This should be done in a test reactor. We would test for cyclability, and also demonstrate that we don't have any auto catalytic failure modes.

As far as the rest of the engine is concerned, I think a radiatively cooled carbon/carbon nozzle should be developed. It has to be nuclear-radiation resistant, erosion resistant, and joined with the pressure vessel.

The key technology for the turbo pump, would be development of carbon/carbon rotors in order to reduce the heating and operate at reactor outlet temperature.

The schedule and costs have been divided into four major tasks before the year 2006: design analysis, technology development, engine test reactor system, and then the GTE, which would be the ground test system (see Figure 11).

The first task is a design analysis which continues through the CDR (Critical Design Review) for the flight test engine. Technology development would include tests, primarily on fuel, coating, and frit materials. The element test reactor would be used to carry out the integrated test on the fuel element.

We estimate that the entire program would cost one and a half billion dollars. Approximately a billion dollars would be required for the program to advance through to the ground test.

In the first year we will develop an engine design compatible with the mission (see Figures 12 and 13). In carrying out this task, we need to follow these philosophies: maximizing the thrust-to-weight or the specific impulse, depending on the system analysis; developing a plan to carry out the proof of principle test; and then of course starting the experimental work.

In phase one, the engine work will be continued. We will demonstrate high temperature particles to meet the mission, demonstrate that we can build hot and cold frits that would meet the mission cyclability, and operate full-scale elements in the test reactor. We would have to carry out a critical experiment. Nobody mentioned a critical experiment yet, but that's a physics test to make sure the physics methods are validated.

In order to develop the fuel element design, one would first carry out electrically heated tests and then eventually nuclear heated tests. Design of the ETR, which is the element test reactor, would be a major effort. There would have to be some work on the carbon/carbon nozzle. Finally the demonstration of carbon-carbon turbine rotors and mixer will be required.

For phase two, we have to select the site for the element test reactor and satisfy all safety requirements (Figure 14). We would prepare the site and then construct and carry out the test. I am sure that there are many other tasks in there, but that's approximately five years away.

As far as major facilities are concerned, critical experiments could be carried out at the available facilities; Los Alamos, or ANL (see Figure 15).

We would have to have a fluid dynamics test facility to check the two phase flow problems involved in start up. A large amount of hydrogen will be required and probably some of the NASA labs would be good candidates for these tests.

An ETR site would have to be selected. It is not clear where one would construct it. It might be concept-specific. I am sure that the test cavity in the middle of the reactor to test concepts would be different depending on the concept. Again, the site for the GTE would have to be selected. Of course, the GTE would be concept-specific, as well.

Finally the GTE might have to have an altitude chamber to simulate start up, particularly if one is going to have a regeneratively cooled nozzle, since the pressure drop must be simulated, implying a sufficiently large nozzle.

In conclusion, we feel that the PBR has several advantages for this mission (Figure 16). High heat transfer allows it to operate at very high power densities for a given total power. Thus we can design a very high-thrust, light-weight reactor. This would be useful if one wants to use redundant engines. Direct cooling of the particles enables one to operate as close as possible to the material limits of the coating. The coolant flow path ensures that all internal components of the reactor, moderator, control rods and so forth operate at inlet temperatures. This ensures reliable operations. And finally we feel that for solid core rockets, this concept would get the closest to the achievable limits, whether one wants to maximize thrust-to-weight or specific impulse.

BIBLIOGRAPHY

Hans Ludewig
PBR Based Concept

1.   Powell, J.R. H. Ludewig, F.L. Horn, K. Araj, R. Benenati, O. Lazareth, G. Slavik. "Nuclear Propulsion System for Orbit Transfer Based on the PBR"; 4th Symposium on Space Nuclear Power System, Albuquerque, NM (1987).

2.   Powell, J.R., H. Ludewig, O.W. Lazareth, F.L. Horn. "Analysis of a Nuclear Orbital Transfer Vehicle Re-entry Accident"; 5th Symposium on Space Nuclear Power Systems, Albuquerque, NM (1988).

3.   Ludewig, H., O. Lazareth, S. Mughabghab, K. Perkins, J. R. Powell. "Small Propulsion Reactor Based on PBR Concept"; 6th Symposium on Space Nuclear Power Systems, Albuquerque, NM (1989).

4.   Horn, F.L., J.R. Powell, J.M. Savino. "Transient Thermal Hydraulic Measurements on PBR Fuel Elements"; 6th Symposium on Space Nuclear Power Systems, Albuquerque, NM (1989).

5.   Lazareth, O., S. Mughabghab, K. Perkins, E. Schmidt, H. Ludewig, J. Powell. "Preliminary Design Considerations of Two Particle Bed Propulsion Reactors Suitable for Mission to Mars," Proceedings of the Case For Mars IV Symposium, Boulder, Colorado (1990).

6.   J. Powell, H. Ludewig, S. Mughabghab, K. Perkins, E. Selcow, E. Schmidt, and F. Horn (BNL), "A Nuclear Thermal Rocket Engine Design Based on the Particle Bed Reactor Suitable for a Mars Mission," AIAA-91-3508, AIAA/NASA/OAI Conference on SEI Technologies, Cleveland, Ohio, September 1991.

SCHEMATIC REPRESENTATION OF
A PARTICLE BED REACTOR BASED ROCKET CONCEPT

FUEL PARTICLE

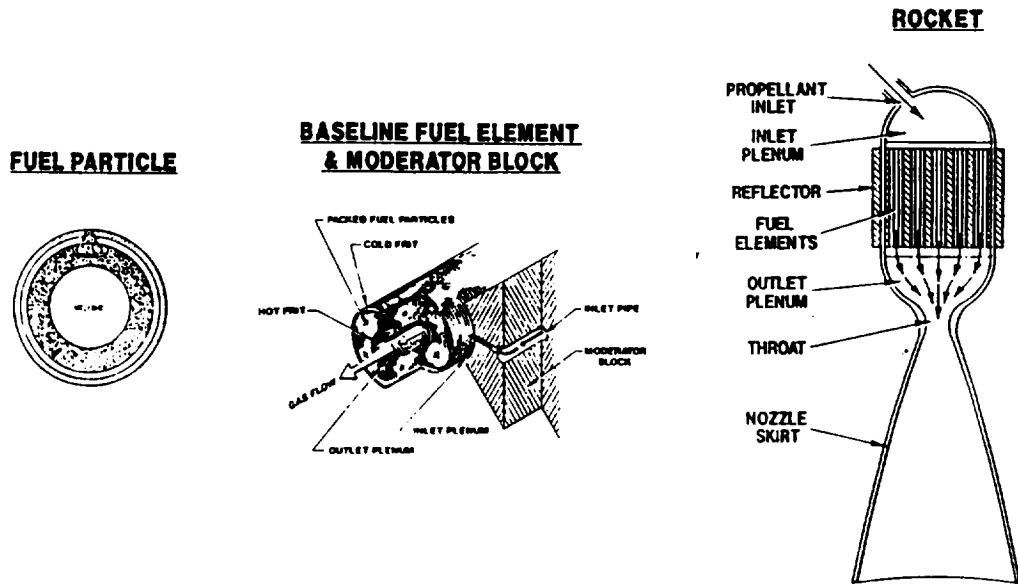**BASELINE FUEL ELEMENT & MODERATOR BLOCK**

ROCKET

Figure 1

DESIGN PHILOSOPHY

- MAXIMIZE THRUST/WEIGHT

  - HIGH POWER DENSITY
  - HIGH PRESSURE
  - HIGH TEMPERATURE
  - SMALL SIZE
  - HIGH THRUST

- MAXIMIZE SPECIFIC IMPULSE

  - LOW POWER DENSITY
  - LOW PRESSURE
  - ULTRA HIGH TEMPERATURE
  - LARGE SIZE
  - LOW THRUST

Figure 2

ENGINE PARAMETERS

	HIGH THRUST/WEIGHT	HIGH SPECIFIC IMPULSE
POWER (MW)	1000 - 5000	500 - 2000
AVERAGE BED POWER DENSITY (MW/L)	20 - 80	5
CHAMBER TEMPERATURE (K°)	2500 - 3500	3000 - 3750
CHAMBER PRESSURE (MPA)	7.0 - 14.0	0.5
SPECIFIC IMPULSE (S)	850 - 1060	1000 - 1300
THRUST (N)	2.0 (5) - 1.0 (6)	6.0 (4) - 2.0 (5)

Figure 3

CALCULATED PARAMETERS

	HIGH THRUST/WEIGHT	HIGH SPECIFIC IMPULSE
TOTAL ENGINE MASS (W/O SHIELD (kg)	650 - 5500	2800 - 6000
THRUST/WEIGHT (W/O SHIELD)	20 - 35	4.0 - 7.5
SHIELD MASS (kg)	1300 - 6400	3700 - 7900
THRUST/WEIGHT (W/SHIELD)	8.6 - 14	2.0 - 3.2
MAXIMUM FUEL TEMPERATURE (K°)	2500 - 3650	3200 - 3900

158

Figure 4

STATUS OF TECHNOLOGY DEVELOPMENT

(BASED ON WORK CARRIED OUT FOR OTV AND MMW PROGRAMS)

	PHYSICS	FLUID DYNAMICS	HEAT TRANSFER	MATERIALS
ANALYSIS	EXPLICIT MONTE CARLO ANALYSIS - MCNP (LA-7396-M) (1986)	1-D SURVEY CODE 1-D TRANSIENT CODE (4TH SYM. ON S.N.P., ALB., NM) (1987)		--
PROOF OF PRINCIPLE EXPERIMENTS	--	PRESSURE DROP CORRELATION ERGUN (CHEM. ENG. PROG. 48:89-97) (1952)	HEAT TRANSFER CORRELATION ACHENBACH' (INT. HEAT TRANS. CONF. MUNICH) (1982)	COMPATIBILITY OF ZrC WITH H, (2ND SYM. ON S.N.P., ALB., NM) (1985)
PROTOTYPE EXPERIMENTS	--	ELECTRICALLY HEATED BLOWDOWN EXPERIMENTS (6TH SYM. ON S.N.P., ALB., NM) (1989)		ZrC COATED FUEL PARTICLES (HOMAN AND KANIA, ORNL/TM-9085, JAN. 1985), (UZr)-C FUEL PARTICLES (SYM. ON CARBIDES IN NUCL. ENG., HARWELL) (1963)

Figure 5

POTENTIAL NEW TECHNOLOGY AND SAFETY REGULATORY IMPACT

- HIGH TEMPERATURE COATING TECHNOLOGY FOR FRITS AND FUEL

- FIBER ENHANCED LIGHT WEIGHT STRUCTURAL MATERIALS
  - LOW Z TO MINIMIZE RADIATION HEATING

- PLATELET CONSTRUCTION OF COMPONENTS TO FACILITATE FLOW CONTROL AND COOLING.

Figure 6

SAFETY ISSUES TO BE ADDRESSED BY ALL NTR CONCEPTS

- FUEL ELEMENT TEST REACTOR SAFETY

- GROUND TEST FACILITY SAFETY FOR AN OPEN CYCLE REACTOR

- RELIABILITY/REDUNDANCY FOR SYSTEM MAN-RATING

- LAUNCH CRITICALITY ACCIDENTS

- EARTH RE-ENTRY ACCIDENTS

- ENERGY RELEASE OF POSSIBLE FAILURE SCENARIOS

- EXTENSIVE SAFETY REVIEW AND DOCUMENTATION EFFORT REQUIRED

Figure 7

POTENTIAL SAFETY ADVANTAGES OF CONCEPT

- COMPACT SIZE AND WEIGHT
  - MULTIPLE ENGINE REDUNDANCY POSSIBLE
  - EASIER TO SHIELD
  - EASIER TO NEUTRONICALLY DECOUPLE MULTIPLE ENGINES

- CONTAINMENT/CONFINEMENT CAPABILITY OF FUEL PARTICLES
  - REDUNDANCY
  - MOST PARTICLES ARE RELATIVELY COOL

- MOST CORE MATERIALS ARE COOL

- USE OF LIGHT-WEIGHT STRUCTURAL MATERIALS MINIMIZES RADIATION HEATING

- THERMAL GRADIENTS ACROSS MOST INDIVIDUAL COMPONENTS ARE SMALL

Figure 8

- HIGH TEMPERATURE PARTICLE/COATING

  - EROSION RESISTANT
  - NEUTRONICALLY BENIGN
  - COMPATIBLE WITH HOT FRIT

- HOT FRIT/COATING

  - EROSION RESISTANT
  - COMPATIBLE WITH PARTICLES
  - ACCEPTABLE MECHANICAL PROPERTIES

- COLD FRIT

  - MANUFACTURABLE WITH VARIABLE POROSITY
  - NEUTRONICALLY BENIGN

- MODERATOR

  - LARGE SELECTION OF MODERATOR POSSIBLE WITH PBR
  - SELECT MODERATOR WHICH WILL BE COMPATIBLE WITH MISSION PROFILE

Figure 9

KEY TECHNOLOGY ISSUES (cont'd)

INTEGRATED FUEL ELEMENT TEST

- DEMONSTRATE ABILITY OF FUEL ELEMENT AND THUS REACTOR TO REPEATEDLY CYCLE IN POWER FROM ZERO TO FULL POWER

- DEMONSTRATE MAXIMUM LIMIT IN ACHIEVABLE BED POWER DENSITY AND HOT CHANNEL FACTORS

- DEMONSTRATE STABLE OPERATION OF ELEMENT, NO AUTOCATALYTIC TEMPERATURE OR FUEL FAILURE MECHANISMS

- CARBON/CARBON NOZZLE - RADIATIVELY COOLED OPTION

  - EROSION RESISTANT
  - JOINT WITH PRESSURE VESSEL

- TURBO PUMP ASSEMBLY

  - CARBON/CARBON ROTORS FOR TURBINE

Figure 10

SCHEDULE AND COSTS

PHASE	I	II	III													

	FY															
ACTIVITY	90	92	94	96	98	00	02	04	06	08	10	12	14	16	18	20	COST ($M)

1. DESIGN AND ANALYSIS

   1ST YEAR   CDR (ETR)   CDR (FTE)   — 30

2. TECHNOLOGY DEVELOPMENT

   COMPLETED TESTS — 50

3. ELEMENT TEST REACTOR

   SITE TESTS CDR PREP. COMPLETED — 320

4. ENGINE DEVELOPMENT AND GTE

   GTE SITE GTE GTE TEST CDR PROPOSED MANUFACTURE COMPLETED — 500

5. SPACE QUALIFICATION

   COMPLETE SPACE QUALIFICATION — 600

   1500

Figure 11

CRITICAL TESTS/ACTIVITIES

- FIRST YEAR

  - DEVELOP ENGINE DESIGN COMPATIBLE WITH MISSION ANALYSIS

  - DEVELOP A PLAN FOR COMPONENT PROOF OF PRINCIPLE AND PROTOTYPIC EXPERIMENTS BASED ON ABOVE DESIGN

  - START EXPERIMENTAL WORK

162

Figure 12

- **CRITICAL TEST - PHASE I**

    - CONTINUE ENGINE DESIGN AND DEVELOPMENT

    - DEMONSTRATE A HIGH TEMPERATURE PARTICLE TO MEET MISSION NEEDS

    - DEMONSTRATE BOTH HOT AND COLD FRITS TO MEET DESIGN GOALS

    - OPERATE A FULL SIZE FUEL ELEMENT IN A TEST REACTOR (TREAT, ACRR)

    - CARRY OUT A CRITICAL EXPERIMENT

    - CARRY OUT PROTOTYPIC ELECTRICALLY HEATED FUEL ELEMENT
      FLOW EXPERIMENT TO DEMONSTRATE REPEATABLE, STABLE
      OPERATION AT MAXIMUM POWER DENSITY

    - DESIGN ELEMENT TEST REACTOR (ETR)

    - DEMONSTRATE CARBON/CARBON NOZZLE

    - DEMONSTRATE CARBON/CARBON TURBINE ROTORS

    - DEMONSTRATE MIXER FOR TURBINE FEED

Figure 13

CRITICAL TESTS/ACTIVITIES (cont'd)

- **CRITICAL TESTS - PHASE II AND III**

    - SELECT SITE FOR ELEMENT TEST REACTOR AND SATISFY ALL
      NECESSARY REGULATORY AND SAFETY AGENCY AND REQUIREMENTS

    - PREPARE TEST SITE FOR ETR AND GROUND TEST ENGINE (GTE)

    - CONSTRUCT AND CARRY OUT FUEL ELEMENT TESTS

    - DESIGN GROUND TEST ENGINE (GTE)

    - CONSTRUCT AND CARRY OUT GTE TEST PROGRAM

Figure 14

<u>MAJOR FACILITIES REQUIREMENTS</u>

- CRITICAL EXPERIMENTS (LANL, ANL (WEST AND EAST))

- FLUID DYNAMICS FLOW FACILITY TO VERIFY TWO-PHASE FLOW AND FLOW INDUCED VIBRATIONS EFFECTS DURING START-UP AND RUNNING

  - MUST HANDLE LARGE QUANTITIES OF HYDROGEN (NASA LABS)

- SITE FOR ETR - NEW

- ETR - NEW MAY BE CONCEPT SPECIFIC

- SITE FOR GTE (SAME AS FOR ETR (?))

- GTE - CONCEPT SPECIFIC

- GTE - ALTITUDE CHAMBER TO TEST START UP

Figure 15

<u>CONCLUSION</u>

- THE PBR HAS SEVERAL UNIQUE ATTRIBUTES WHICH MAKE IT ATTRACTIVE AS A PROPULSION REACTOR

  - HIGH HEAT TRANSFER AREA ENABLES REACTOR TO OPERATE AT HIGH BED POWER DENSITIES

  - FOR A GIVEN TOTAL POWER, THE HIGH POWER DENSITY RESULTS IN A SMALL AND THUS LOW MASS REACTOR - USEFUL IF REDUNDANT ENGINES ARE DESIRED

  - DIRECT COOLING OF PARTICLES RESULTS IN THE HIGHEST POSSIBLE GAS TEMPERATURE FOR ANY PARTICLE DESIGN - DESIRABLE FOR MAXIMIZING SPECIFIC IMPULSE

  - COOLANT FLOW PATH ENSURES THAT THE MODERATOR CONTROLS (INTERNAL OR EXTERNAL) AND MOST STRUCTURAL COMPONENTS OPERATE AT COOLANT INLET TEMPERATURES - ASSURES A WIDE SELECTION OF MODERATORS, ENSURES RELIABLE OPERATION OF CONTROL RODS AND STRUCTURAL COMPONENTS

- THESE ATTRIBUTES WILL RESULT IN A REACTOR DESIGN WHICH SHOULD APPROACH THE PRACTICALLY ACHIEVABLE LIMITS OF SPECIFIC IMPULSE AND THRUST/WEIGHT RATIO FOR A SOLID CORE REACTOR DESIGN

Figure 16