# OPEN CYCLE GAS CORE NUCLEAR ROCKETS

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I am going to walk you through some prior Lewis Research Center work. The work started about 32 years ago, and ended about 17 years ago, so this is not something that was done yesterday. However, that's true of everything we are talking about. It was part of a supporting research and technology program funded out of SNPO, the Space Nuclear Propulsion Office. It was not a development program like NERVA. Work was done at Lewis on the open cycle Gas Core concept, and parallel work was also funded by NERVA money, done at United Aircraft Research Laboratory. That work will be described in the following paper by Tom Latham.

The basic concept is shown in Figure 1. The open cycle gas core engine is a nuclear propulsion device. Propulsion is provided by hot hydrogen which is heated directly by thermal radiation from the nuclear fuel. This is the entire engine. Critical mass is sustained in the uranium plasma in the center. It has typically 30-50 kilograms of fuel. It's a thermal reactor in the sense that fissions are caused by absorption of thermal neutrons. The fast neutrons go out to an external moderator/reflector material and, by collision, slow down to thermal energy levels, and then come back in and cause fissions.

The hydrogen propellant is stored in a tank. It runs through a turbo pump system, regeneratively removes all of the gamma and neutron heating in the moderator/reflector region, cools the nozzle and then flows into a cavity.

There is a direct contact in this open-cycle concept between the uranium and the hydrogen. The transfer of heat is primarily by a photon wave, a thermal flux that radiates outward. It is intercepted by the hydrogen propellant that comes in through the wall so that it's optically black in there. The wall doesn't see this very high-temperature incandescent nuclear plasma. The heat is intercepted by the hydrogen at low temperatures by adding what is called seed material. Seed material is very small dust particles which could be carbon, tungsten, or U235 itself. The hydrogen becomes optically opaque and begins to absorb the radiation. The hydrogen flow path is generated through the wall at controlled angles. The hydrogen depends on the flow field setting up essentially a stagnation pressure point which causes a slow recirculation dead zone in the center. That's why the uranium "sits" there instead of escaping. A lot of work was done on the fluid dynamics of how you set up a flow pattern to cause that to happen.

The advantage of the concept is very high specific impulse because you can, in principle, take the plasma to any temperature you want to by increasing the fission level by withdrawing or turning control rods or control drums.

The model you might picture is very much like a small contained "sun," radiating its heat outward, with very high temperatures in the center of the plasma. Temperature is fairly constant near the center, but drops near the edges and then drops through the hydrogen. The heating process is fission, not fusion, so it is not really like a sun. It is an optically-thick, radiating, incandescent heat source. In principle, you can reach any specific impulse that the hydrogen can attain without burning out the nozzle or the wall.

The nuclear issues are: containment of the plasma, the nuclear criticality effects, the power levels, and the control system. The hydrodynamics are mainly related to flow. The heat transfer concerns the seeding of the hydrogen and the protection of the wall and the nozzle.

The work was following a step-wise path which involved neutronics, fluid dynamics and heat transfer (Figure 2). We had not progressed to the point of moving beyond the neutronics, fluid dynamics and heat transfer, and beginning to couple those things together. The work stopped in 1973. There were cold critical experiments, fluid dynamics experiments, and heat transfer experiments done. The heat transfer experiments concentrated on the optical properties of the gases themselves when they were ionized. In 1973, cold flow experiments were beginning which combined the understanding of cold flow and nuclear issues into a cold flow critical experiment. There were also hot flow experiments that combined RF heating with the cold flow. The next step would have been bringing together all three of those in small-scale fission experiments, and then a full-scale test equivalent to running a NERVA engine out in Jackass Flats. There was, right near the end of the program, a PER (Preliminary Engineering Report Study), which began to look at how you would really test one of these things on the ground when you got to where you knew how to build one.

The work was done primarily at Lewis Research Center, but it was supported by a large number of relatively small research grants and contracts. Figure 3 shows who the actors were, what they were doing in the areas of criticality, radiative heat transfer, nuclear fuel containment and systems studies. The A designates analytical work, the E is for experimental work.

Figure 4 shows a list of new technologies that could be used in the development of the open cycle engine. The flow was one of the big problems experimentally. We were always out in front of the analytical techniques that could be used to analyze those kinds of experiments. CFD could help a lot by modeling some of the old cold flow data and hot flow data. Maybe we could model the entire engine concept itself. CFD techniques have advanced a lot since 1973. Also, structural ceramics didn't even exist then. Space radiators and heat pipes have also advanced a lot since the days this work was done by Lewis Research Center. Non-intrusive instrument technology would be very valuable in the flow experiments.

The key questions haven't changed at all in 15 or 20 years (Figure 5). Can containment

be achieved? That's a tricky question. Primarily it comes down to an acceptable fuel loss rate. And there are a lot of semantics in what is acceptable -- cost, public perception, using up a natural resource, safety and radiation. And the amount of fuel that is in the reactor, of course, determines the pressure level. The next question is could a 5,000 second Isp nozzle be cooled even if you could heat the hydrogen? This is a key problem we really didn't address. Finally, can it be ground tested within today's constraints and at an acceptable cost and risk? It is easy to write the questions down, but difficult to answer them. However, it is not difficult to envision ways to get at the answers.

Base line engine performance for a 5,000 megawatt reactor is shown in Figure 6; 5,200 seconds specific impulse, 50,000 pound thrust, engine weight 250,000 pounds. The entire engine was contained within about a 14-foot pressure vessel. Nozzle area ratio was about 50 to 1, but it could be whatever you chose.

Man rating features required nothing special in this engine other than the usual turbo pump duality and things like that. The engine weight included the pressure shell, moderator and reflector (which actually constituted the shielding). The gamma rays are all trapped by the large mass around the fuel.

The mission/systems status of the work that was done by Lewis as of about 1973 showed the potential for a 60- to 80-day round trip mission, which did not deliver a payload ("courier" mission), to Mars (Figure 7). Performance was unmatched, unsurprisingly, by NERVA and nuclear electric, but somewhat surprisingly even by fusion, because of the way Lewis modeled fusion on that very first trip.

An engineering design study of an engine in about 1972 disclosed areas for potential improvement primarily in terms of what the fuel would be. It is not necessarily conclusive that you use Uranium 235; you might use 233. Other improvements could affect moderator/reflector material, the liner itself, the inside liner that the hydrogen flows through, and finally the space radiator. A first cut through that preliminary engineering report study disclosed no real fundamental reasons that you can't test a gas core reactor.

Engine/mission characteristics are show in Figure 8. It's for the Mars "courier" mission. Specific impulse is shown as a function of engine thrust and this is total engine weight.

The nominal engine picked for the mission was 50,000 pound thrust. Isp is reduced because you have to cool the nozzle transpirationally and that led to the reference engine. It took about a 100,000 pound command module and left a 600 kilometer Earth orbit. It parked into an eccentric Mars orbit with about 1.1 Mars-radius, came back, and reparked into the same 600 kilometer Earth orbit. Figure 8 is for that mission. It shows trip time versus the initial mass in Earth orbit in kilograms, from zero to two million. Trip time follows the kind of curve that you would expect. You can cut initial mass in

Earth orbit in half by going out 80 days from 60.

Figure 9 shows what ought to be done. First year activities would be to setup the CFD models, looking at both thermal Isp limits, and the containment and flow process. Also, you would reestablish an engine system model to give you a crack at the trade-off studies between weight, pressure, and critical mass as a function of Isp level. Then, you should go back and update that 1972 facility study.

In the near term (maybe the first year or two), one critical experiment would be to reestablish a benchmark cold flow test (Figure 10). I would urge moving into a five to ten megawatt RF heated Isp nozzle test.

A one-megawatt RF flow containment test would also be valuable. Technology to do that was already demonstrated at the end of the program. Finally, a spherical ZPR (zero power reactor) test using flow within the cavity should be run.

For long-term critical testing, you would have to do a flowing critical test to show containment and reactivity control (Figure 11). First cold, then warm, then hot. Also, you should perform a low-power engine test (a reactor test) to show the Isp and effluent handling capability. Finally, run a full power prototype engine test.

What would all that cost? Figure 12 shows a guess. Start up studies at first should retrieve the original data. Come up with a preliminary program plan and then a final program plan. Then, in what is perhaps an optimistically short time period, technology development starts where the program ended before and moves fairly fast to a point I call "technology readiness." Technology readiness means you don't need any more new technology, any more research in creating new knowledge. What you do need is a lot of engineering to develop the system.

The big bucks are spent on engine development. This items includes an early cut at redoing the PER on the facility, then do an official PER as a part of the usual NASA Construction of Facilities procedure, begin ground testing and finally reach some point at which the engine is ground-qualified. At this point, it is as qualified as you can do in a one-g environment. Because you are at such high pressure levels, you really don't need to exhaust into a vacuum. The biggest factor here may be the presence of a one-g field in an engine that would be operating more like 0.1 to 0.01g. You can't simulate that, so then there is space development required.

Figure 13 breaks out the costs as to how much you would spend to get to key decision points.

Assuming you start this fall, by next spring with a fairly small expenditure you can gather the old data base and take a better look at what I am discussing here. If this is a serious contender at the research level then initiate the focused technology program

development around the spring of 1992. By that point would you have spent a million dollars.

Spring of 1993 would bring you up to a "go, no go" decision based on the facility PER and the high Isp nozzle cooling test. You spend five million bucks or so to get to that point.

Then you step up the expenditure level around 1997. You would be halfway through ground development and at that point you would have enough information to make some kind of a decision.

At about this point, you reach the end of the technology readiness plan where you don't intend to develop any more technology. Only engineering remains. Around 2000, 2002 you would decide how well the solid core is going, how well does the Gas-Core Nuclear Rocket look like it is being developed?

Figure 14 shows a test facility. I have assumed all the way through this that you wouldn't be working on gas cores unless you are working on solid cores, so the basic facility would be there. You would need to add a very large scrubber (which in today's environment you need for Solid-Core reactor anyway) to the engine test.

What are the risks? There are two kinds of risks: One is programmatic-which may be tough to deal with (Figure 15). First of all, the time to technology readiness. It takes a lot of guts to buy into this program and invest the money you need to before you know if you are going all the way. I think that's a risk. Other risks include public reactions to fuel release in space, and getting ground testing approval. I think those are very significant program risks, especially for this kind of concept.

Then there are technical risks. I put these in my opinion of order of priority. These risks include nozzle cooling, nonnuclear simulation reliability, fuel containment and reactor dynamics, and ground testing and scrubbers.

After 15 years of research at Lewis Research Center I think the idea remains very attractive (Figure 16). Obviously the idea of high-speed, low trip-times to Mars is very attractive. The key questions for the open cycle are: Can containment be achieved, can it be ground tested and can a rocket nozzle handle 5,000 seconds Isp flows? Finally, I think restarting the effort with a reasonable efficiency would be a fun challenge for somebody.

A VOICE: Why does it weigh so much and what ideas do you have to bring the weight down?

MR. RAGSDALE: It weighs so much because of the radiator, moderator, and reflector material around it and the pressure vessel that has to contain it. The way you can bring

it down would be devise ways that don't require as much mass. I don't really think you are ever going to bring the weight down very much. You just need that much moderator material around it to thermalize the neutrons.

A VOICE: What is the moderator material?

MR. RAGSDALE: Beryllium, beryllium oxide, heavy water, possibly graphite.

A VOICE: Perhaps zirc hydride on that nozzle could be more effective?

MR. RAGSDALE: Possibly, but I think you are not going to significantly affect the weight. These things are just big and heavy.

A VOICE: Half of your engine weight was radiator.

MR. RAGSDALE: Right. And today's technology may provide lighter radiators. I am not sure that the weight is a fantastic problem. The real question in my mind is not bringing the weight down but does it really work and produce 5,000 seconds of impulse. If it does, you are going to get to Mars and back in 60 or 80 days. Even if you made the weight zero, you are not going to do a lot better than that.

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Open Cycle Gas Core

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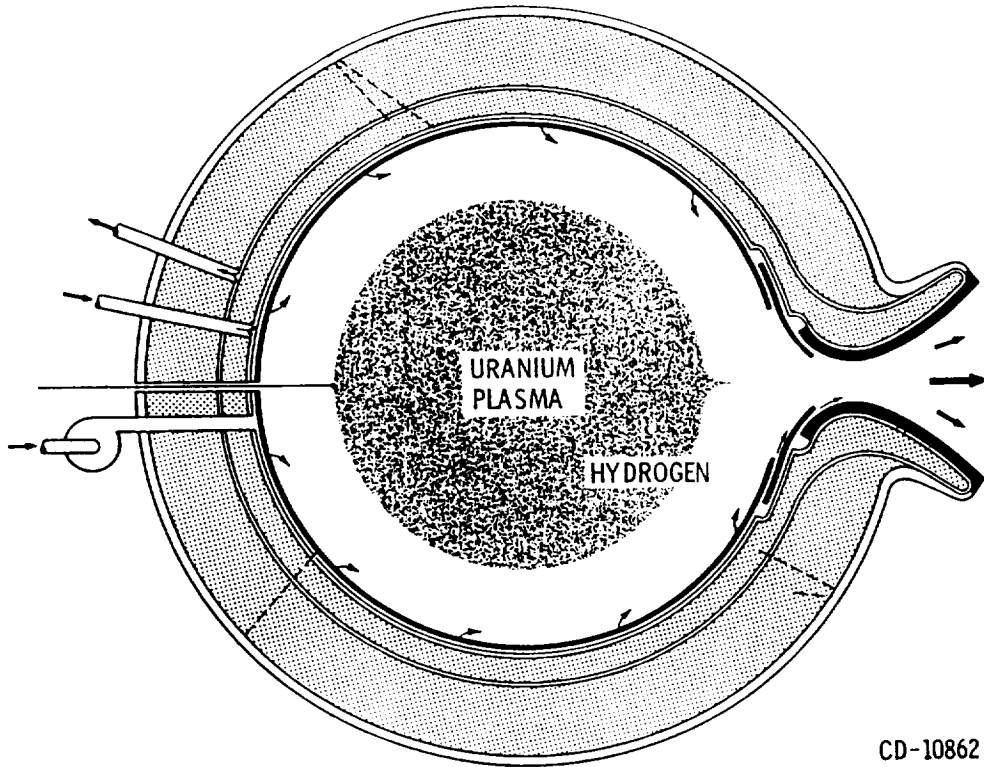
# OPEN CYCLE GAS CORE ENGINE - THE CONCEPT



URANIUM
PLASMA

HYDROGEN

CD-10862

**Figure 1**

# THE WORK WAS FOLLOWING A STEPWISE PATH



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                        CONCEPT

    NEUTRONICS        FLUID DYNAMICS        HEAT TRANSFER

  COLD STATIC          COLD FLOW        OPTICAL PROPERTIES,
  CRITICAL EXPTS.     EXPERIMENTS        RF EXPERIMENTS

          COLD FLOW              HOT FLOW
        CRITICAL EXPTS.         EXPERIMENTS          [1973 STATUS]

              SMALL-SCALE FISSION
              HEATED EXPERIMENTS            (PER STUDY)

              FULL-SCALE FISSION
              HEATED EXPERIMENTS

              FLIGHT ENGINE
              GROUND TESTS
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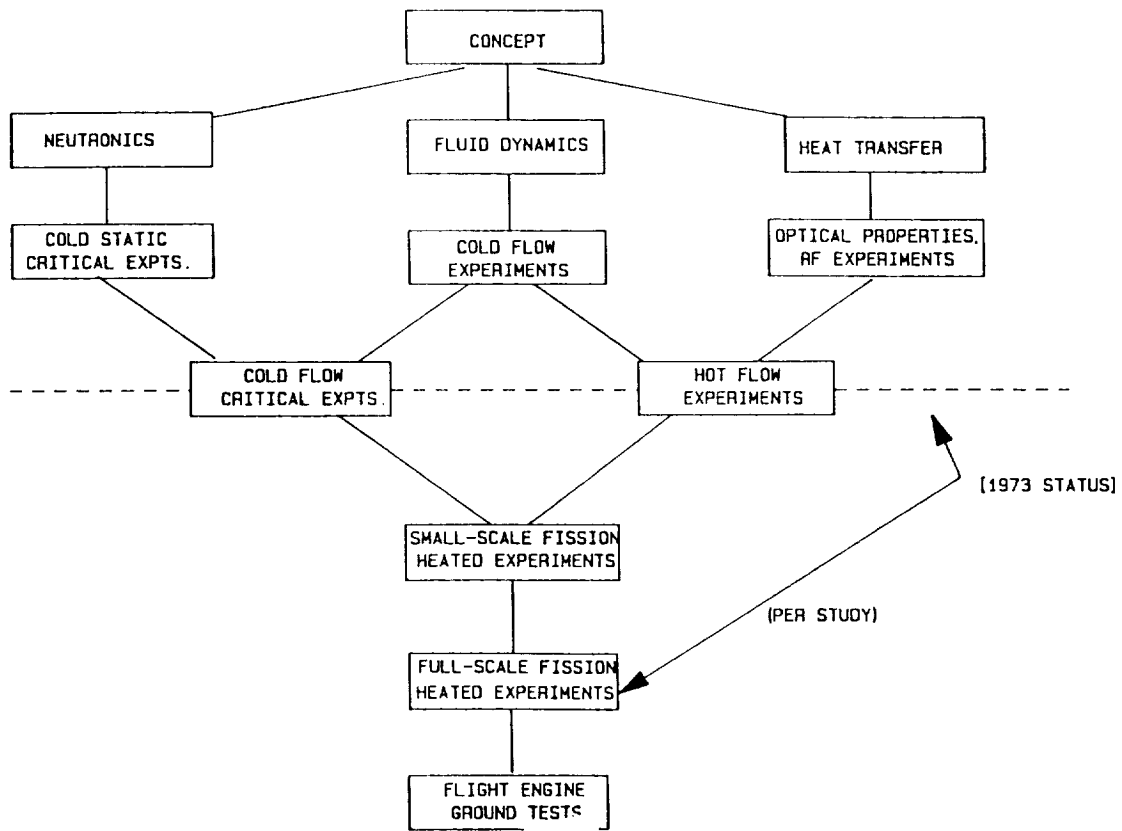
**Figure 2**

## WHO DID WHAT

| Criticality of Gaseous Fuel | Radiative Heat Transfer | Nuclear Fuel Confinement | Systems Study |
|---|---|---|---|
| NASA-Lewis (A) | NASA-Lewis (A/E) | NASA-Lewis (A) | NASA-Lewis (A) |
| Aerojet Nuclear (E) | TAFA Division Humphreys Corp. (E) | Illinois Institute of Technology (A/E) | United Aircraft Research Labs (A) |
| United Aircraft Research Labs (A) | Georgia Institute of Technology (E) | Cornell University (A/E) | Georgia Institute of Technology (A) |
| Versar, Inc. (A) | AEDC (E) | United Aircraft Research Labs (A/E) | University of Florida (A) |
| | United Aircraft Research Labs (A/E) | Aerojet Nuclear (E) | Computer & Applied Sciences, Inc. (A) |
| | University of Florida (E) | University of Arizona (E) | |
| | University of Maryland (E) | NASA-Ames (E) | |
| | NASA-Langley (E) | | |

**Figure 3**

## POTENTIAL NEW TECHNOLOGY IMPACTS

o COMPUTATIONAL FLUID DYNAMICS
   - MODEL OLD COLD FLOW EXPERIMENTAL DATA
   - MODEL OLD RF HOT FLOW DATA (?)
   - MODEL THE ENGINE CONCEPT FLOW

o STRUCTURAL CERAMICS

o SPACE RADIATORS/HEAT PIPES

o NON-INTRUSIVE INSTRUMENTATION
   - COLD FLOW
   - HOT FLOW

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**Figure 4**

# KEY QUESTIONS

* CAN CONTAINMENT BE ACHIEVED ?

    - ACCEPTABLE FUEL LOSS RATE

    - ACCEPTABLE REACTOR PRESSURE

* CAN A 5000 SEC Isp NOZZLE BE COOLED ?

* CAN IT BE GROUND TESTED ?

    - WITHIN TODAY'S CONSTRAINTS

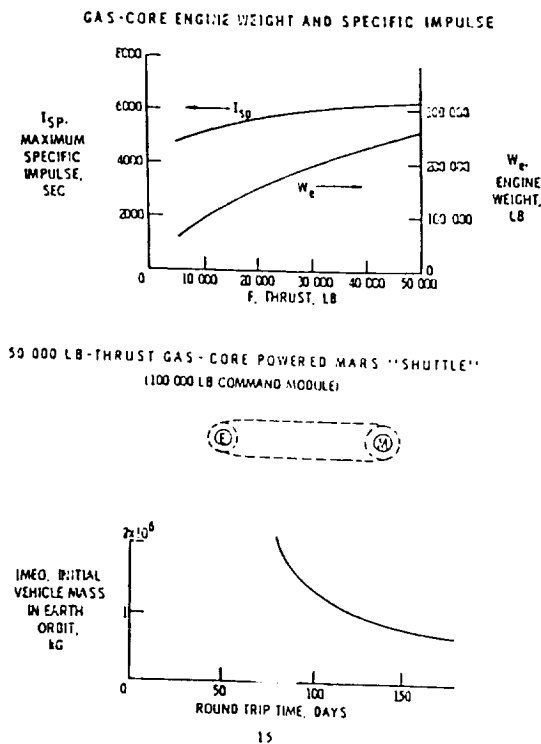    - ACCEPTABLE COST/RISK

Figure 5

# BASELINE ENGINE PERFORMANCE DATA

| | |
|---|---|
| SPECIFIC IMPULSE | 5200 SEC |
| THRUST | 50,000 LB |
| ENGINE WEIGHT | 250,000 LB |
| ENGINE DIAMETER ( sphere ) | 14 FT |
| NOZZLE AREA RATIO | 50:1 |

MAN RATING FEATURES - nothing engine-unique
is included - usual pump duality, etc, is assumed

* includes pressure shell, moderator, reflector, shielding,
space radiator

Figure 6

o   MISSION STUDIES SHOWED POTENTIAL FOR 60-80 DAY
    ROUNDTRIP COURIER MISSIONS TO MARS - PERFORMANCE
    UNMATCHED BY NERVA, NUCLEAR-ELECTRIC, OR FUSION
    SYSTEMS


o   AN ENGINEERING DESIGN STUDY OF AN ENGINE
    DISCLOSED AREAS OF POTENTIAL IMPROVEMENT -
    FUEL, MODERATOR, LINER, RADIATOR


o   A FIRST CUT AT A GROUND TEST FACILITY (A "PER"
    STUDY) BY LeRC DISCLOSED NO INSURMOUNTABLE
    ISSUES, BUT LEFT MUCH TO BE DONE


**Figure 7**



GAS-CORE ENGINE WEIGHT AND SPECIFIC IMPULSE

50 000 LB-THRUST GAS-CORE POWERED MARS "SHUTTLE"
(100 000 LB COMMAND MODULE)

# ENGINE/MISSION CHARACTERISTICS

**Figure 8**

# KEY FIRST YEAR ACTIVITIES

* SET UP CFD MODELS

    - THERMAL Isp LIMITS

    - CONTAINMENT

* ESTABLISH ENGINE SYSTEM MODEL

    - WEIGHT, PRESSURE, CRITICAL MASS, Isp

* UPDATE 1972 FACILITY PER STUDY

**Figure 9**

# CRITICAL TESTS - NEAR TERM

* BENCHMARK COLD FLOW TEST

* 5 - 10 MW Isp NOZZLE TEST

* 1 MW RF HOT FLOW CONTAINMENT TEST

* SPHERICAL ZPR TEST OF CFD FUEL DISTRIBUTION

**Figure 10**

# CRITICAL TESTS  -  LONG TERM

* FLOWING CRITICAL REACTOR TEST TO SHOW
  CONTAINMENT AND REACTIVITY CONTROL

  - COLD, THEN HOT

* LOW POWER ENGINE TEST TO SHOW Isp and
  EFFLUENT HANDLING
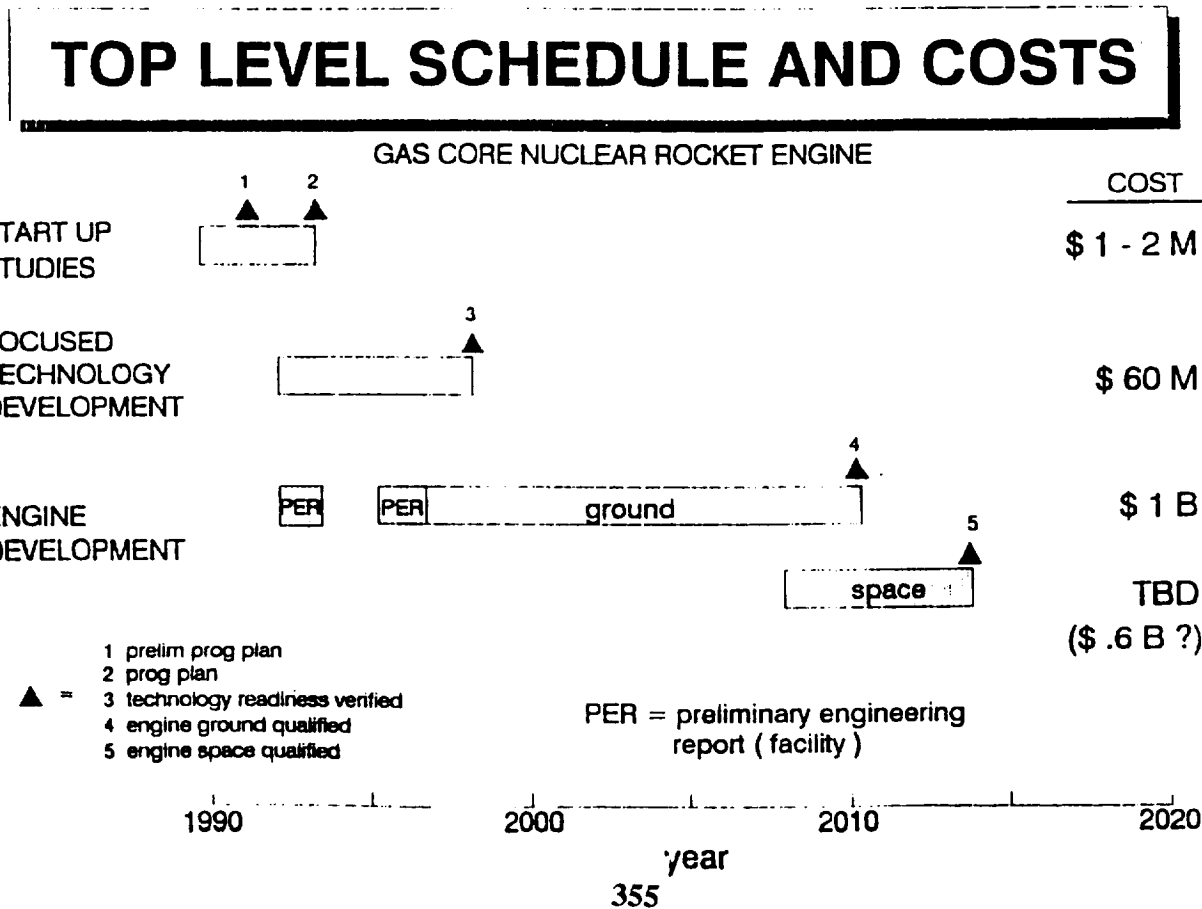
* FULL POWER PROTOTYPE ENGINE GROUND TEST

Figure 11

# TOP LEVEL SCHEDULE AND COSTS

### GAS CORE NUCLEAR ROCKET ENGINE

| | | COST |
|---|---|---|
| START UP STUDIES | 1 ▲  2 ▲ | $ 1 - 2 M |
| FOCUSED TECHNOLOGY DEVELOPMENT | 3 ▲ | $ 60 M |
| ENGINE DEVELOPMENT | PER  PER  ground  4 ▲ | $ 1 B |
| | space  5 ▲ | TBD ($ .6 B ?) |

▲ =
1  prelim prog plan
2  prog plan
3  technology readiness verified
4  engine ground qualified
5  engine space qualified

PER = preliminary engineering
report ( facility )

1990        2000        2010        2020

year

Figure 12

# MAJOR DECISION POINTS

| DATE | DECISION | COST TO DECISION |
|------|----------|------------------|
| APR 1991 | RETAIN/DROP GNR OPTION | $ 200 K |
| SPRING, 1992 | INITIATE FOCUSED TECHNOLOGY DEVELOPMENT | $ 1 M |
| SPRING, 1993 | GO-NO-GO DECISION BASED ON FACILITY PER & NOZZLE Isp TESTS | $ 5 M |
| 1997 | INITIATE ENGINE DEVELOPMENT BASED ON TECHNOLOGY READINESS ASSESSMENT | $ 75 M |
| 2002 | SOLID CORE/GNR DECISION | $ 700 M |
| 2008 | INITIATE SPACE QUALIFICATION | $ 1 B |

Figure 13

# ENGINE TEST FACILITY
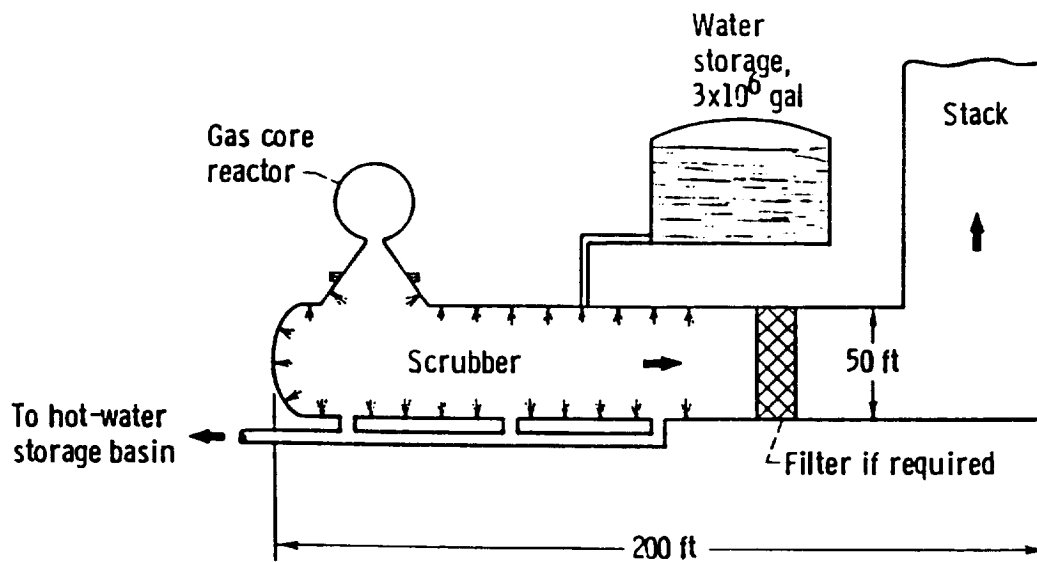


CD-10403-22

Figure 16. - Addition to test stand ETS-1 or test cell C at Nuclear Rocket Development Station required for 10 000-megawatt gas core test facility. Hydrogen and services supplied by existing systems.

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Figure 14

# DEVELOPMENT RISKS

PROGRAMATTIC

    * TIME TO TECHNOLOGY READINESS DEMO

    * REACTIONS TO FUEL RELEASE IN SPACE

    * GROUND TESTING APPROVALS


TECHNICAL

    * NOZZLE COOLING

    * NON-NUCLEAR SIMULATION RELIABILITY

    * FUEL CONTAINMENT/REACTOR DYNAMICS

    * GROUND TESTING - SCRUBBERS

Figure 15

# CLOSING REMARKS

●    AFTER 15 YEARS OF RESEARCH, THE IDEA REMAINS VERY
ATTRACTIVE, BUT HIGH RISK

●    THE KEY QUESTIONS FOR THE OPEN CYCLE GNR ARE :

        - CAN CONTAINMENT BE ACHEIVED ?
        - CAN IT BE GROUND TESTED ?
        - CAN A ROCKET NOZZLE HANDLE HIGH
          PRESSURE, HIGH Isp FLOWS ?

●    RESTARTING THE EFFORT WITH REASONABLE EFFICIENCY
WOULD BE AN EXCITING CHALLENGE !

Figure 16