

LIQUID ANNULUS

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As seen in Figure 1, the specific impulse varies as the square root of the temperature and inversely with the square root of the molecular weight of the propellant. Typical values for specific impulse corresponding to various rocket concepts are shown.

The Liquid Annulus core concept consists of a fuel elements which will be arranged in a moderator block. What is shown in Figure 2 is still a single element. The element rotates about its axis (Figures 2, 3, and 4), with the inner surface molten.

Inlet hydrogen gas enters one end, which would be the left side on Figure 2 (may or may not be seeded), flows down the channel picking up heat and exits the other end at 5,000 - 6,000 K. The moderator in this case is beryllium. The other elements would be arranged in a hexagonal pattern; all of them rotating.

The overall coolant path is down through the beryllium, cooling it and then back up through an annulus surrounding the element and then through the hot section. This concept is based on an experiment carried out by Grosse in 1963. He carried out an experiment in which he used liquid alumina and achieved a temperature of over 3,500 K in the central cavity. Figure 4 shows a detail of the Grosse experiment and we see a sectional view of the element. The inner layer would be liquid and the second would be a solid layer backed up by the structural components.

These are the advantages we see for the system (see Figure 5): high specific impulse; structural material will all run at low temperature; lower fission product inventory because of evaporation.

Size estimates were carried out on the concept (see Figure 6-7). Heat radiates from the surface and depends on the temperature. The power is dependent on the emissivities and view factors. Estimates of these figures were obtained from NASA publications. We use emissivity of 0.4 - 0.8 for our reactor designs.

Using these heat fluxes one can layout a reactor design. We picked seven elements, and basically these are the parameters: 200 megawatts; 7 elements; and a length to radius ratio of 24 (see Figure 7) per element. Once one falls below 5,000 K the reactor gets very massive and the concept loses its appeal. We really have to operate above a temperature of 5,000 K.

Figure 8 shows the reactor parameters for emissivities of $f = 0.4$ and 0.8 ; 200 megawatts; 6,000 degrees; ten atmospheres pressure; and seven elements. The fuel element radius (see Figure 9) varies depending on the thickness of the fuel bed. The pitch in both cases

is 30 centimeters, the diameter of the total reactor is 110 cm.

We have carried out some first order analysis of heat transfer. However, there is still a lot of work to be done in the analysis of a rotating dissociating gas.

New technologies in fuel development will require investigation of the binary or ternary alloys. i.e., (U,Zr)C and (U,Zr,N6)C. Finally enhanced light weight structures are important. Platelet technology would be useful in a nozzle.

As far as technology issues are concerned (see Figure 10), we need to understand the fluid dynamics and heat transfer of the rotating fuel element. We also need to know about the mass transfer from the surface. Depending on how fast one rotates it, it could act as a centrifuge, but this still has to be studied.

There has to be a mechanism for rotating the elements. A gas bearing at the top to act as a thrust bearing is needed. Nuclear data needs to be acquired at these elevated temperatures.

The values in Figure 11 are the mission parameters for this concept. We would be looking at specific impulses in the range of 1,600-2,000 seconds. The only reason there is a range here is due to the uncertainty of how much uranium will evaporate and end up in the outlet stream. If it is an extreme amount it might be more in the 1,600 range, in which case the concept will lose some of its appeal. About 2,000 seconds is probably the desirable level.

For this particular engine we are talking about 200 megawatts. The approximate thrust level is 20000 N, and the engine mass is about 3,000 kilograms. The other engine would be a little lower depending on the value for emissivity that we use. The thrust to weight level is approximately unity. Without a shield it will be twice that, maybe three times.

Multiple starts and stops in this particular concept are not a problem. In this case one does not require the gas to pass through the liquid, which could freeze. It goes along the surface, so we should be able to start this without any trouble.

Depending on the operating time, one might want to take uranium along and add it to the fuel region, or at least to the seed material. It can be added to the reactor as it is running. It depends on how low the thrust is and how long the operating time is. This is really a mission dependent requirement.

There are five schedule and cost areas that will have to be worked: design; technology; element test reactor; and engine development for the ground; and space qualification. We estimate a cost of around about 1 to \$2 billion (see Figure 12).

The really important activity would be the fuel element test. If this is not successful then

there is no point in going further. Even at this level one could probably discern whether it is a worthwhile technology or not.

The first year we would develop a plan to test the fluid dynamics and heat transfer in that the rotating element. In phase one we would continue the design work, and we would demonstrate the heat and mass transfer of the prototypic fuel element (see Figure 13).

We would certainly want to carry out a critical experiment. It is not quite clear how one would do that for a system such as this because there would also be a requirement to verify the nuclear properties at the elevated temperatures. Some work will have to be carried out on the nozzle. It is not clear how to design such a nozzle; maybe platelet technology with transpiration cooling.

For phase two and phase three (see Figure 14), we would have to select the test site. This experiment would be very stringent because of the guarantee of losing fission products. An efficient scrubber system would be required.

Critical experiments can be carried out, however, I would like to point out that the machines will have to be modified quite dramatically to do a critical on this reactor. See Figure 15 for the rest of the facility requirements.

As a conclusion, we feel that this concept is worth at least a first look because of the promise of very high specific impulse. Because of the low thrust one would probably need a cluster of engines. This is not necessarily bad because there would be some redundancy, but because of the low thrust one might have to refuel while running. Again, depending on the fuel vaporization, material can be included in the uranium that is injected as one is running along.

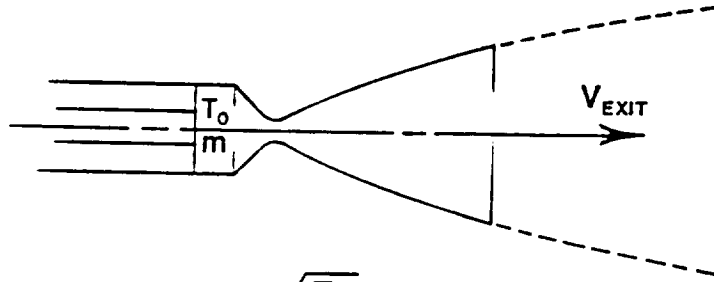
BIBLIOGRAPHY

Hans Ludewig LARS Based Concept

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WHY LIQUID CORE ?

HIGHER I_{sp} ;
 T NOT LIMITED BY T_{MELT} OF FUEL



$$I_{SP} \propto V_{EXIT} \propto \sqrt{\frac{T_0}{m}}$$

<u>ROCKET TYPE</u>	<u>I_{SP} sec</u>
CHEMICAL	150-450
SOLID CORE NUCLEAR	800-1200
LIQUID CORE NUCLEAR	1500-2000

Figure 1

LARS CONCEPT

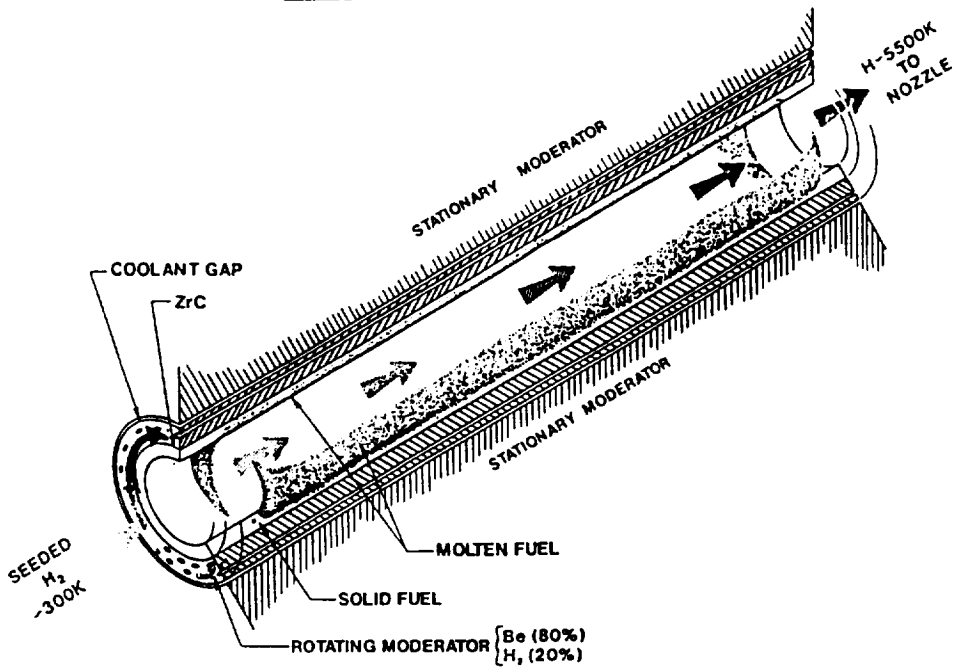


Figure 2

LARS CONCEPT (CONT'D)

KEY FEATURES:

1. MOLTEN FUEL CONTAINED IN ITS OWN MATERIAL.
2. LAYERS STABILIZED BY CENTRIPETAL FORCE.
3. HYDROGEN IS DISSOCIATED AT HIGH T LEADING TO HIGH I_{sp} .

NOTE:

ROTATIONAL CONTAINMENT OF LIQUID REFRACTORIES BY COOLED SOLID OUTER LAYER HAS BEEN DEMONSTRATED BY A. V. GROSSE (Science, 1963).

Figure 3

LARS ROTATING FUEL ELEMENT

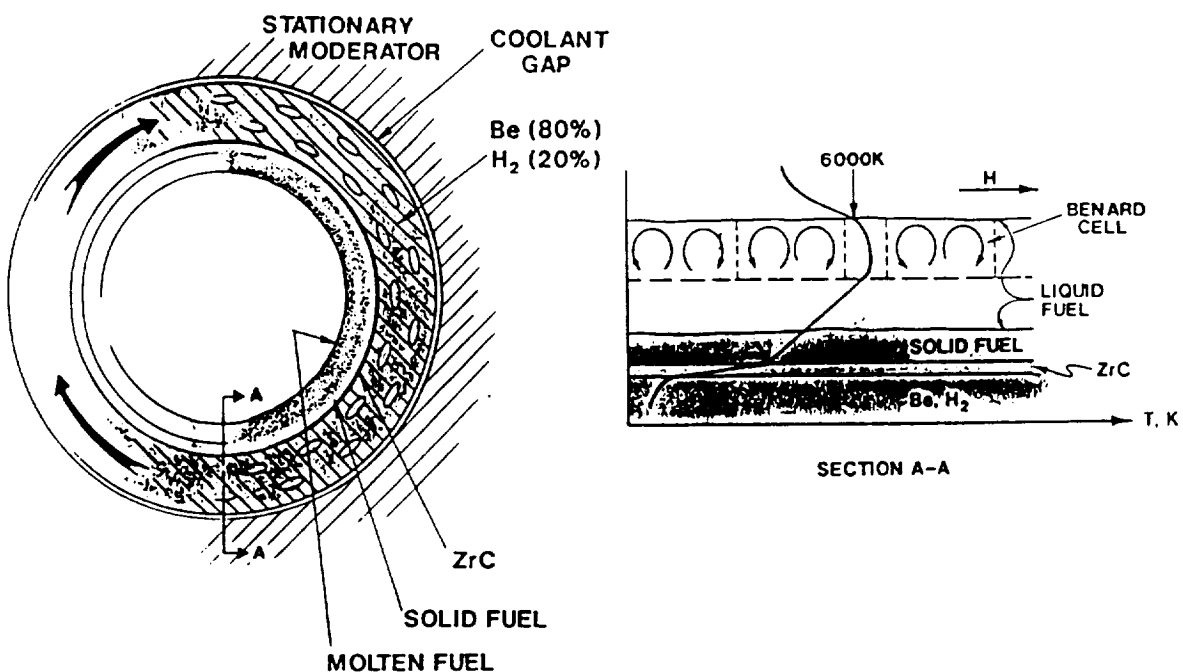


Figure 4

- LARS ADVANTAGES -

- HIGH SPECIFIC IMPULSE
- NO STRUCTURAL ELEMENTS OPERATE AT ELEVATED TEMPERATURES
- POTENTIALLY A SELF-CLEANING REACTOR SYSTEM - FISSION PRODUCTS EVAPORATED INTO DIRECTED EXHAUST STREAM, REDUCING FISSION PRODUCT INVENTORY
- LOWER FISSION PRODUCT INVENTORY REDUCES AFTER HEAT AND COOLANT REQUIRED TO REMOVE AFTER HEAT

Figure 5

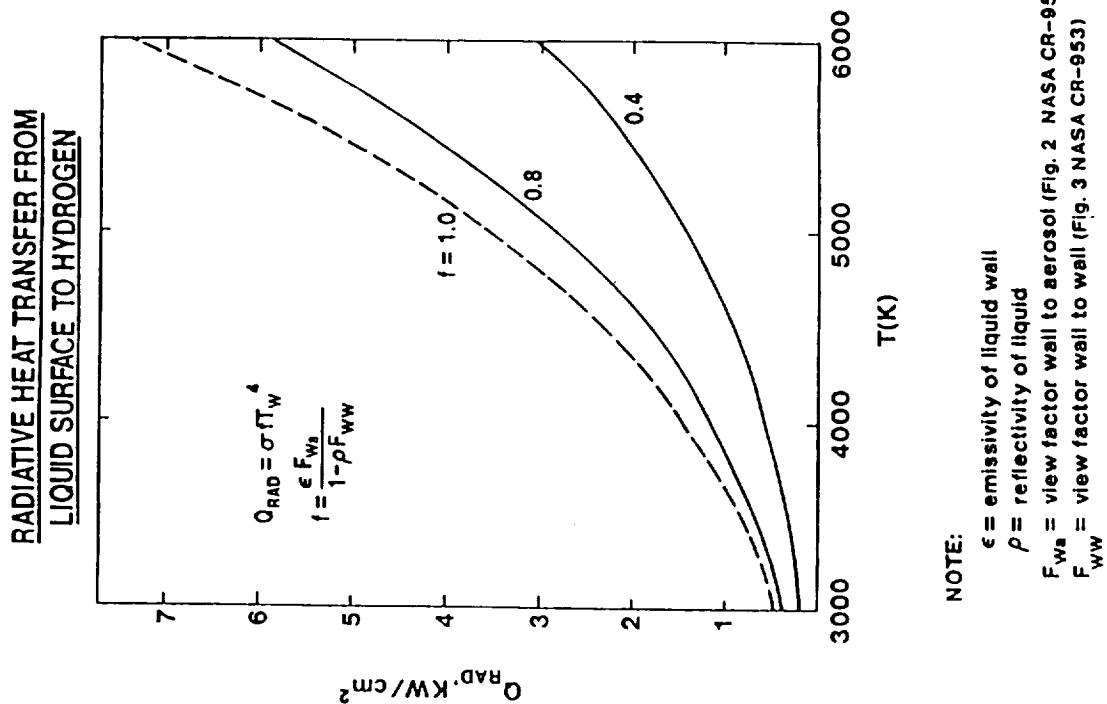


Figure 6

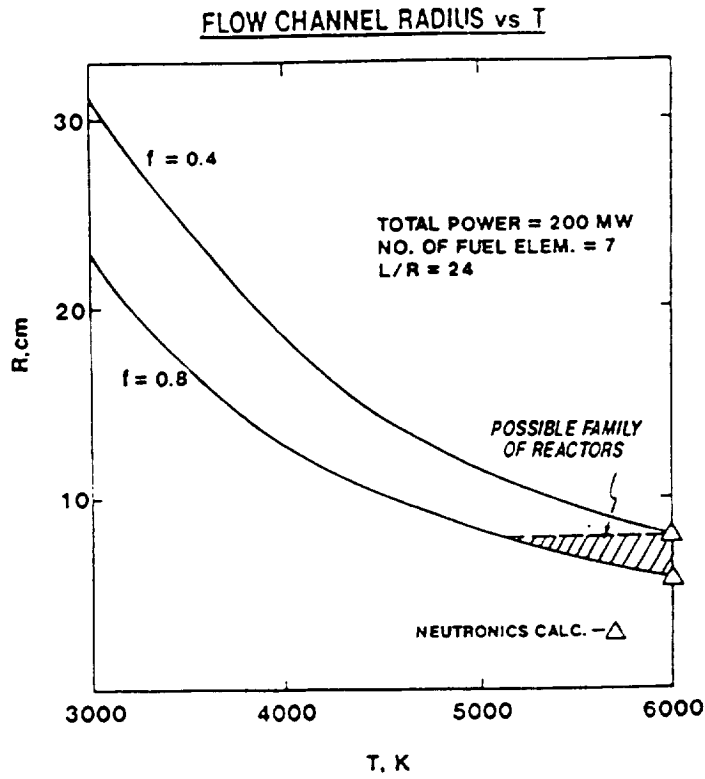


Figure 7

REACTOR PARAMETERS

	$f = 0.4$		$f = 0.8$	
TOTAL POWER (MW)	200.	6000.	200.	6000.
OUTLET TEMPERATURE (K)	10.	7	10.	7
OUTLET PRESSURE (ATM)	8.0	8.0	5.6	5.6
NO. OF ELEMENTS	9.4	8.1	8.1	8.1
OUTLET DUCT RADIUS (CM)	12.4	11.1	11.1	11.1
FUEL BED RADIUS (CM)	30.0	30.0	30.0	30.0
ROTATING DRUM RADIUS (CM)	110.0	110.0	110.0	110.0
ELEMENT PITCH (CM)	192.7	135.5	135.5	135.5
REACTOR O.D. (CM)	3.0	3.0	3.0	3.0
REACTOR HEIGHT (CM)	5.0	5.0	5.0	5.0
TOP REFLECTOR (CM)	10.0	10.0	10.0	10.0
BOTTOM REFLECTOR (CM)	30.0	30.0	30.0	30.0
RADIAL REFLECTOR (CM)	1.08	1.10	1.10	1.10
MASS OF UC, (KG)				
MULTIPLICATION FACTOR, K_{eff}				

Figure 8

LARS CROSS SECTION

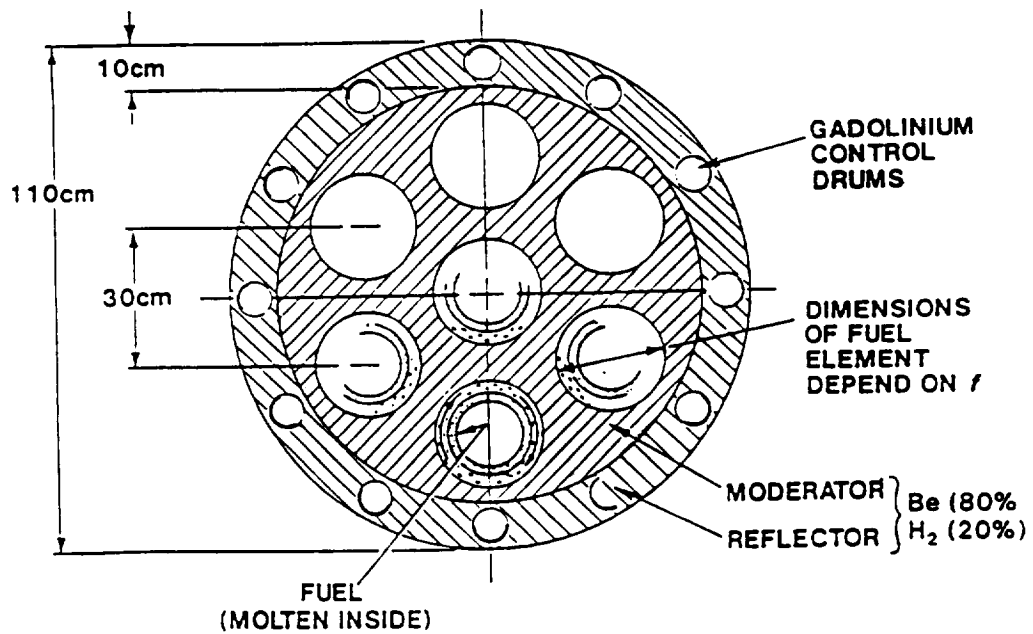


Figure 9

KEY TECHNOLOGY ISSUES

- ANALYTIC AND EXPERIMENTAL UNDERSTANDING OF COOLANT BEHAVIOR IN OUTLET DUCT - BOTH FLUID DYNAMICS AND HEAT TRANSFER
- ANALYTIC AND EXPERIMENTAL UNDERSTANDING OF MASS TRANSFER FROM MOLTEN FUEL SURFACE TO PROPELLANT STREAM
- DEVELOPMENT OF ROTATING MECHANISM AND GAS THRUST BEARING
- NUCLEAR DATA AT ELEVATED TEMPERATURES

Figure 10

KEY MISSION PARAMETERS

SPECIFIC IMPULSE(S)	1600 - 2000
THRUST (N)	2.0 (4)
ENGINE MASS (kg)	3000
REACTOR POWER (MW)	200
THRUST/WEIGHT	1.0

- **MULTIPLE STARTS AND STOPS SHOULD NOT POSE ANY PROBLEM SINCE PROPELLANT PASSES OVER MOLTEN SURFACES RATHER THAN THROUGH THE MOLTEN LAYER**
- **STORAGE OF URANIUM BEARING POWDER MAY BE REQUIRED - DEPENDING ON RUN TIME**

Figure 11

SCHEDULE AND COSTS

PHASE	I			II			III			FY										COST (\$M)			
	90	92	94	96	98	00	02	04	06	08	10	12	14	16	18	20							
1. DESIGN AND ANALYSIS	1ST YEAR			CDR (ETR, GTE)			CDR (FTE)													30			
	√	√		√					√														
2. TECHNOLOGY DEVELOPMENT				COMPLETED TESTS																50			
	√			√																			
3. ELEMENT TEST REACTOR				SITE TESTS			CDR PREP. COMPLETED													350			
	√			√	√	√																	
4. ENGINE DEVELOPMENT AND GTA				SITE PREP. TEST			GTE MANUFACTURE			GTE TEST COMPLETED													570
				√		√		√				√											
5. SPACE QUALIFICATION													√										600
																	1600						

Figure 12

CRITICAL TEST/ACTIVITIES

- **FIRST YEAR**
 - **DEVELOP ENGINE DESIGN COMPATIBLE WITH MISSION ANALYSIS**
 - **DEVELOP A PLAN FOR PROOF OF PRINCIPLE AND PROTOTYPIC EXPERIMENTS**
 - **START EXPERIMENTAL WORK**

- **CRITICAL TESTS - PHASE I**
 - **CONTINUE ENGINE DESIGN AND DEVELOPMENT**
 - **DEMONSTRATE HEAT AND MASS TRANSFER IN A PROTOTYPIC FUEL ELEMENT BOTH ELECTRICALLY AND NUCLEAR HEATED EXPERIMENTS.**
 - **CARRY OUT CRITICAL EXPERIMENT - VERIFY NUCLEAR DATA AT OPERATING TEMPERATURES**
 - **VERIFY NOZZLE DESIGN**
 - **DESIGN ETR**

Figure 13

CRITICAL TEST/ACTIVITIES (cont'd)

- **CRITICAL TESTS - PHASES II AND III**
 - **SELECT SITE FOR ETR AND GTE AND SATISFY REGULATORY AND SAFETY REQUIREMENTS**
 - **PREPARE SITE**
 - **DESIGN AND CONSTRUCT ETR AND GTE**
 - **CARRY OUT ETR AND GTE TEST PROGRAM**

Figure 14

FACILITY REQUIREMENTS

- CRITICAL EXPERIMENT FACILITY (LANL, ANL (WEST AND EAST))
- FLUID DYNAMICS FLOW FACILITY (NASA LABS)
- SITE FOR ETR - NEW, WILL REQUIRE ALLOWANCE FOR FISSION PRODUCTS IN EXHAUST
- ETR - NEW, MAY BE CONCEPT SPECIFIC
- SITE FOR GTE
- GTE - CONCEPT SPECIFIC
- GTE - ALTITUDE CHAMBER TO TEST START UP

Figure 15