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THE ARMOUR DUST FUELED REACTOR (ADFR)*

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The ADFR is based upon the use of a new fuel form — fissionable dust carried in a gas. This fuel form offers promise of a major economic advance through the use of 2,000 - 3,000°F operating temperature and a low-cost fuel cycle.

The ADFR concept was described at the 1958 Nuclear Engineering and Science Conference (1). Since then a development program has been initiated under AEC contract to investigate experimentally the proposed fuel and study analytically other reactor characteristics. Following a brief review of the concept, this development program (2, 3), is described below.

ADFR CONCEPT

The ADFR fuel is an aerosol type suspension that approximates the uniformity and handling ease of a gas. The core can be simply a block of ceramic moderator material such as graphite or beryllium oxide with through holes for passage of the fuel laden gas. For chemical compatibility, if graphite is used as the moderator, the fuel dust would be uranium carbide, the ducts and chambers in contact with the fuel could be lined with a carbide such as silicon carbide, and the gas would be helium. If beryllium oxide is used as the moderator, the fuel dust would be uranium dioxide, the lining material could be aluminum oxide, and the gas carbon dioxide. These systems are referred to respectively as the carbide and oxide systems.

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Figure 1 shows a flow diagram of the AHTR system. All ducts are lined with ceramic thermal insulation and covered with a gas tight metal skin. High temperature fluid leaves the core and plenum chamber and enters a cyclone separator which removes all particles substantially larger than the fuel particles. These might arise from decomposition of the ceramic lining. The fluid next enters a heat exchanger or boiler in which useful heat is extracted. The heat exchanger could be a conventional metallic boiler with 2,000 - 3,000°F reactor fluid replacing at the same temperature combustion gas for the generation of steam at typical power plant temperatures. For higher temperature process heat a ceramic heat exchanger would be required. Following the heat exchanger, most of the flow enters a blower and is recirculated, while a small fraction of the flow is passed through a fission product removal system. In this system, following cooling and settling of the larger particles, an electrostatic precipitator is used to remove all particulate matter. All other gases are then removed from helium by adsorption and freezing in a low temperature charcoal bed. Carbon dioxide may be separated by freezing or simply discarded. Clean gas from this system is returned to the primary loop through the blower seals. An expansion chamber, connected to the lower plenum chamber through a pressure regulator, is used to damp power fluctuations. The pressure regulator would permit rapid movement of fuel into the expansion chamber to terminate a power transient. Fuel would return slowly to the system through an orifice.

An internally cooled AHTR core has also been considered since it yields a non-radioactive primary loop for ease of maintenance and reduced fuel inventory. In this case the core resembles a shell-and-tube type heat exchanger

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with fuel laden gas on one side and pure gas on the other. The fuel is circulated at low velocity through the core and fission product cleanup system. The pure gas serves as a coolant and is circulated at high velocity through the core and remainder of the primary loop. High neutron economy is retained by constructing the core tubes of moderator material. Some leakage of gas through these tubes into the fuel region can be tolerated as it will be removed in the fission product cleanup system. Power density is more limited than in the externally cooled case first discussed but compares very favorably with other gas cooled reactors due to the high operating temperatures.

FUEL DUST EXPERIMENTS

The characteristics of circulating gas-dust suspensions have been studied in a loop constructed of 2 inch diameter glass tubing that measures about 5 ft x 5 ft. A photograph of this loop is shown in Figure 2. The dust is introduced by simply allowing it to fall into the circulating gas from the sealed dust feeder. Changes in dust concentration are monitored by using a light source and photocell to measure light transmission and relating these readings to dust concentration. A manometer across the blower indicates pressure drop around the loop. The dust laden gas passes through the blower which is mounted in an insulated box used to reduce the noise level. The small blower mounted on top of the box provides ventilation for cooling the dust circulation blower. Gas velocities of about 100 ft/sec, depending somewhat upon dust concentration, have been achieved with the blower shown in Figure 2. This blower is driven by a 3/4 hp motor. In addition, a 3 hp blower has been used to obtain a gas velocity of 147 ft/sec.

Tests Using 3 hp Blower

The 3 hp blower was first used since high gas velocities are desirable in a reactor system. In order to provide more ready comminution, it was decided to use initially an innocuous simulant for the UO_2. Aluminum oxide was chosen and the smallest particle size readily obtainable was used. This size is 100 mesh or about 10 microns average size. Again for ease of use, and also because the loop cannot be pressurized, it was decided to use atmospheric pressure air to simulate helium at about 7 atm pressure. In an HTGR system a pressure of at least 10 atm would be used.

Dust concentrations up to 0.1 vol per cent were used. This concentration is roughly twice that required for criticality of the reference reactor described below under reactor typics. The dust dispersed readily upon introduction into the air stream and circulated well with very little wall deposit. The concentration of circulating dust decreases for about 10 minutes until an equilibrium is reached after which it remains constant. This decrease is believed due to a dynamic collection of dust in the blower and can probably be substantially reduced by proper blower design. Stopping the blower results in almost all the dust gradually accumulating in the blower as it comes to rest. Upon restarting the blower the concentration of circulating dust gradually builds up and again after about a 10 minute transient equilibrium is established. The restarting transient is shown as curve A of Figure 3. In curve B of Figure 3, the loop has been restarted with additional powder added simultaneously. The equilibrium concentration is seen to be proportional to initial loading. All dust concentrations are relative since it requires about 1 minute to load the dust into the loop and during this time collection as well as entrainment is taking place.

operation with the 3 hp blower was limited to periods of about a half-hour due to excessive heating. After 2 hours of total operation the blower case was opened for inspection. There was no evidence of a hard deposit. The only signs of erosion were a slight polishing of the blower case walls and the end of the rotor shaft at the intake.

Tests Using 3/4 HP Blower

The 3/4 hp blower was next used to run in longer periods of continuous operation. These have been increased to a maximum of 6 hours and are limited only by the desire to conserve the life of the blower motor which was not designed for continuous operation. The variation of dust concentration with time using this blower is similar to that previously obtained with the large blower. Following dust addition to the loop there is at first a rapid decrease in circulating dust concentration with approximate equilibrium reached after about 15 minutes. For the next 30 minutes the concentration decreases very slowly to a true equilibrium which is then maintained. A concentration of 0.1 vol per cent, or 50 grams, of aluminum oxide was generally used.

After about ten hours of total operation the blower was dismantled for examination. Both the blower case and rotor are of cast aluminum and thus relatively soft. However, the only evidence of erosion was a polishing of the tips of the rotor. There was very little dust deposit on the blower case walls. The glass walls of the loop have shown no evidence of erosion and also very little wall deposit.

A series of tests were made in which gas velocity, blower speed and pressure drop across the loop were measured at different aluminum oxide dust loadings. Blower speed and pressure drop showed only slight variation with dust loadings up to 0.2 vol per cent, but gas velocity decreased linearly from 115 ft/sec with clean air to 71 ft/sec with the 0.2 vol per cent loading. However, earlier work with the 3 hp blower did not indicate a significant decrease in gas velocity with dust loading and thus this appears to be a function of blower design and capacity. The 0.2 vol per cent dust concentration is the highest that has been circulated. Although this high concentration was circulated for only a short period, it is interesting to note that no difficulties were experienced, either in entraining this amount of dust or otherwise.

In addition to the aluminum oxide experiments, some work has also been done with UO_2. For this work all joints in the loop were a clad and the entire loop e closed as shown in Figure 2. Nitrogen was chosen as the carrier gas for UO_2 rather than air to ensure against oxidation of the particles to higher oxides. A small amount, 10 gm, of micronized powder, approximately 1 micron average size, was put into the circulating nitrogen. This small amount was used in anticipation of the possibility of excessive wall deposit, which proved to be the case. Very soon after entering the gas stream the particles plated out rather uniformly over the glass walls of the loop. Following this some larger size UO_2 particles, average size 5 microns, were introduced into the loop and these were found to circulate well and behave in general like the previously used 10 micron aluminum oxide. In fact, after a few minutes the 5 micron material cleaned the 1 micron particles

from the straight sections of the loop. The elbow deposit seen in Figure 2 is probably the 1 micron material. Up to 10 grams of 5 micron UO_2 powder have been added to the loop. The concentration of circulating dust reaches an equilibrium, as with the aluminum oxide powder, and remains constant thereafter.

REACTOR PHYSICS

Criticality calculations have been performed for a series of graphite moderated and reflected, U^{235} fueled AMFR cores to determine fuel concentration requirements. These calculations have used the two-group reactor model and were performed on an IBM 650 computer. All parameters were evaluated at 2,000°F. A reference design which gives a reactor of moderate size with a low fuel dust concentration is shown in Table 1. The ends of the reactor core have been assumed to be bare, although the plenum chambers will contribute some end reflection. The thermal neutron radial flux distribution in the reference design shows a variation from the center to the edge of the core of only 18 per cent due to the large migration area of this reactor type. This uniformity, together with the high thermal flux resulting from light fuel loading and high power density, makes the AMFR attractive as a test reactor. As an example of the attainable flux level, if the reference design is operated at 500 mw, the average thermal flux in the core is 1.6×10^{15} n/cm^2-sec. The conditions required for operation at 500 mw are given below under Thermodynamics.

The variation of critical fuel concentration with per cent of the core devoted to fuel channels shows a minimum at about the 45 per cent value chosen for the reference design. Other parameters that have been examined for their effect on the fuel concentration required for criticality are core diameter and height and reflector thickness. The effect of varying these

around the reference design is shown in Figure 4. It can be seen that further substantial reductions in fuel concentration can be accomplished by increasing any of the reactor dimensions. The use of U^{233} as fuel also reduces the required fuel concentration. A calculation using U^{233} in the reference design, which is not optimized for U^{233}, shows a critical mass of 12.8 kgm and a fuel concentration of 0.035 vol per cent. The high neutron economy of the ARTR indicates that breeding is likely using the U^{233}-thorium cycle.

For all of these calculations the core was assumed homogeneous. A one-group calculation of the flux within a fuel channel, which showed negligible flux depression due to the very light fuel concentration, justifies this assumption. The effects of fast fission or the presence of fission products were not considered.

THE COOLANT

Since the energy release occurs via fine particles in the coolant stream relatively little, perhaps 15 per cent, of the energy reaches the channel walls. Also, heat transfer from the channel walls back to the fluid is excellent due to the high temperatures and radiation absorption of the particles. Thus the channel wall temperatures are expected to be only 50°F - 100°F above the bulk fluid temperature. This reduces power density calculations in the core to those of simple heat transport. An example can be cited for the reference design core using helium as the carrier gas, a pressure of 30 atm, and inlet and outlet temperatures of 1,000°F and 2,500°F respectively. For the removal of 500 mw of heat an average gas velocity of 220 ft/sec is required. Even higher gas velocities, and corresponding power levels, are believed to be practical.

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The large temperature rise through the core of the ARFR and the nature of the fuel will cause a considerable axial variation in fuel concentration. The calculation of this effect was simplified by considering the core as divided axially into a number of regions having uniform properties. The equations describing neutron flux, power, and temperature were solved in each region by the application of the critical conditions and the requirements of continuity of neutron flux and neutron current at the interface between adjacent regions. These calculations show that the effects of fuel non-uniformity in the ARFR are of small consequence. For example, one case which assumed a rise in temperature of 1,500°F across the core showed the neutron flux distribution still to approximate closely the usual cosine shape with the peak shifted from the midpoint about 7 per cent of the core height toward the inlet. The power distribution was more skewed with its peak shifted from the midpoint about 25 per cent of the core height toward the inlet. However, the axial power distribution is of little interest for the ARFR since such a large fraction of the heat appears directly in the fluid.

SAFETY

The ARFR is believed to be unusually safe, due in part to the absence of chemical reactants and liquids which may be rapidly converted to gases and in part to the large prompt temperature coefficient of reactivity of the fluid fuel. Of course, the accidental addition of fuel dust to the core will result in a transient and this condition has been studied for two assumptions regarding the capabilities of a pressure regulator. The use of control rods to reduce the transient has not been considered.

If the pressure regulator is assumed to be perfect, the pressure will not change during the disturbance and only the temperature will rise. This

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rio, is given by the temperature coefficient of the excess reactivity inserted. The prompt temperature coefficient of the fuel has been calculated to be $-1.63 \times 10^{-4}\,°C^{-1}$ on the basis of carrier gas expansion and resulting change of fuel density with temperature. The variation of excess reactivity with excess core fuel content was computed by means of the same two-group code used for the criticality calculations. This was done for the reference design shown in Table 1 and the results appear in Figure 4 as curve . In this curve the maximum case of a excess addition of 5 per cent of the total critical core loading is shown, this is seen to result in 4.7 per cent excess reactivity. Combining this with the above temperature coefficient gives a temperature rise of 512°F, which is not large compared with the calculated operating temperatures.

In order to bracket the case in which a mechanical pressure regulator is used, it was next assumed that there is no pressure regulator and further that the core and plenum chambers constitute a sealed system. A simplified model of the gas dynamics was used which assumed that an interface is maintained between the fluid originally from the core and that in the plenum chambers during the short time required to reach peak power. Thus, expansion of the core as fuel out of the core is resisted by the fluid compressed in the plenum. Also, the conservative assumption was made that the fluid originally in the core continues to be heated throughout the transient. The volume of the plenum chambers together was taken as equal to the core volume. Excess fuel was considered to be added instantaneously, with peak power reached when the excess fuel is removed from the core due to fluid expansion. For the reference design reactor, operating initially at 50 mw, the time to reach peak power, and the increase in pressure and temperature at peak power from initial values are shown respectively as curves A, B, and C in Figure 5.

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Again considering an excess addition of 20 per cent of the critical mass, the pressure and temperature increases are seen to be 13.5 atm and 1,700°F from initial values of 30 atm and 2,000°F, with the power peak reached in 14.5 msec. These values can probably be tolerated and would be decreased not only by the pressure regulator but also by expansion into the external system. For ultimate safety a rupturable diaphragm could be used in addition to the pressure regulator between the reactor system and the expansion chamber.

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2. ARF Quarterly Progress Report No. 1, USAEC contract AT(11-1)-603.
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MAJOR POTENTIAL ADVANTAGES

HIGH TEMPERATURES

Temperatures of 2,000 - 3,000°F enable not only the efficient production of electric power, but also the application of reactor heat to a wide range of endothermic chemical processes. It also yields high reactor power density and thus reduced fuel inventory and capital costs.

SOLID CARRIER

The carrier gas comprises greater than 99.9 per cent by volume of the fluid fuel. If helium is used, corrosion is limited to 1 particles in the helium, fission products, and the fuel dust.

LOW COST REPROCESSING

Reprocessing costs are expected to be substantially reduced due to the ease of separation of the carrier gas from the particles. Thus only the particles (fuel and solid fission fragments) need be chemically processed. Fission gases are removed in concentrated form by means of a low temperature charcoal bed which may be used as a radiation source.

HIGH NEUTRON ECONOMY

The reactor core is virtually free of neutron poisons due to the absence of control rods, fuel element matrix and cladding material, structural material, and much of the fission products. Breeding therefore seems assured using the Th - U^{233} cycle.

FLUID FUEL ADVANTAGES

In common with other fluid fuel systems the ADER has the following important advantages: (a) No fuel element fabrication costs, (b) Unlimited burnup, (c) No control rods, and (d) Continuous operation and cleanup.

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TABLE 1

REACTOR DESIGN

Core	Right circular cylinder, radially reflected
Height:	10 feet
Diameter:	6 feet
Reflector Thickness:	2 feet
Fuel	93 per cent enriched U^{235} as UO_2
Critical Mass:	17.4 kgm U^{235}
Fuel/Channel Volume Ratio:	0.0507 per cent
Fuel/Moderator Atom Ratio:	146.7 ppm
Channels:	Axial through core, occupying 45 per cent of core volume
Gas	Helium
Moderator and Reflector	Graphite
Density:	1.476 gm/cm
Temperature	2,000°F uniform through core and reflector

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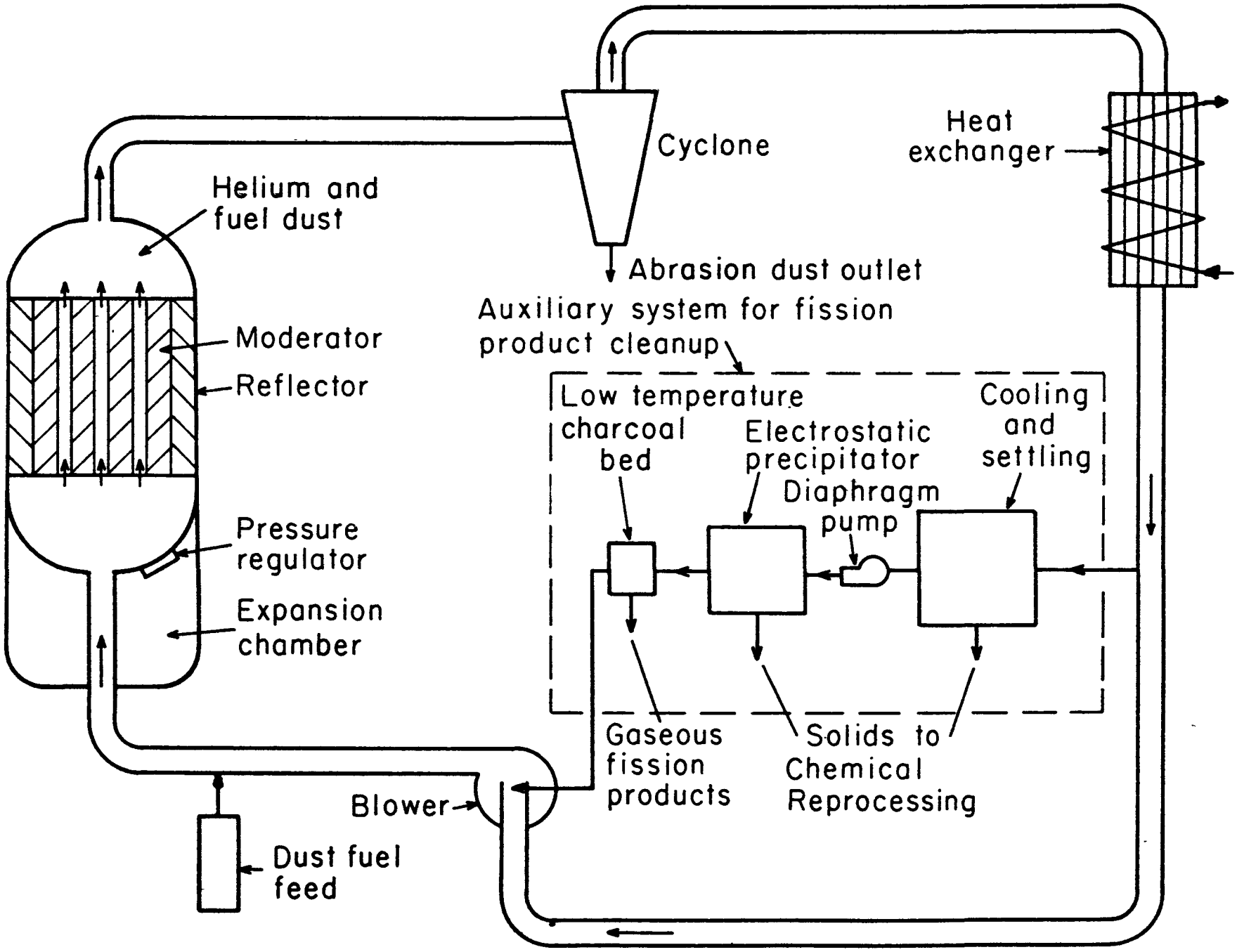

Fig.1 ADFR flow system.

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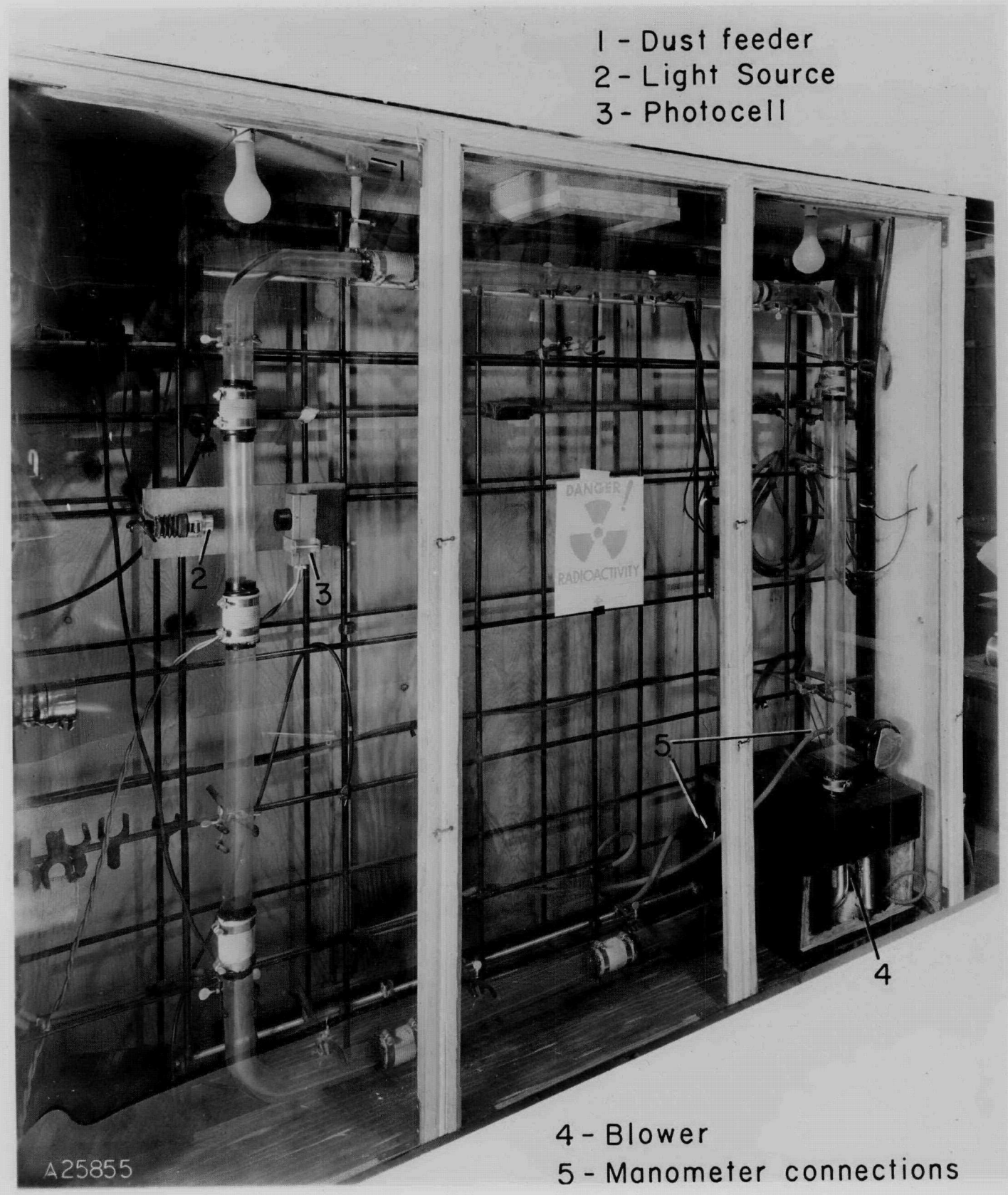

Fig. 2 Dust loop after circulation of UO_2 in nitrogen, blower off.

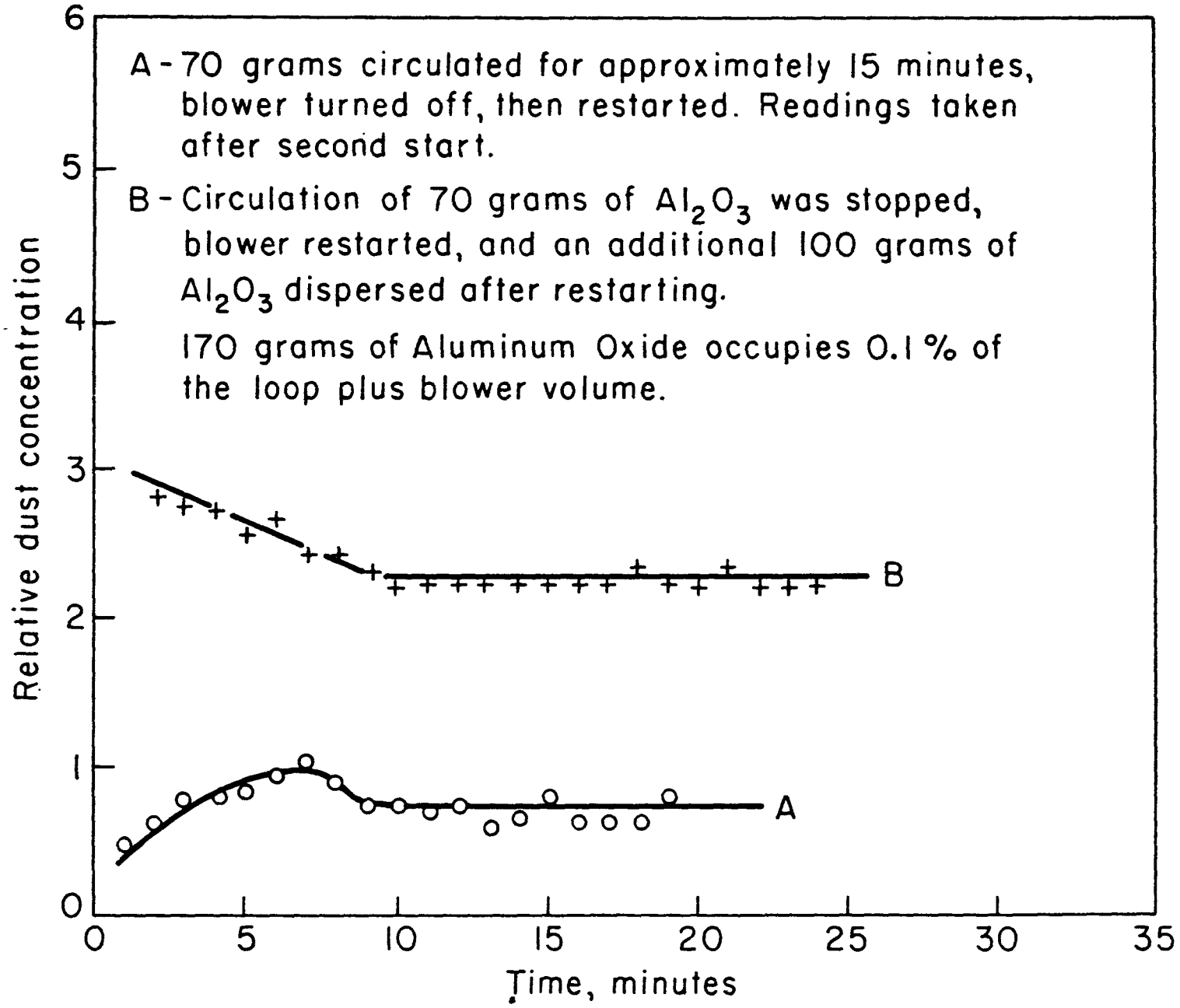

Fig. 3 Photocell data for aluminum oxide circulated by the 3 hp blower.

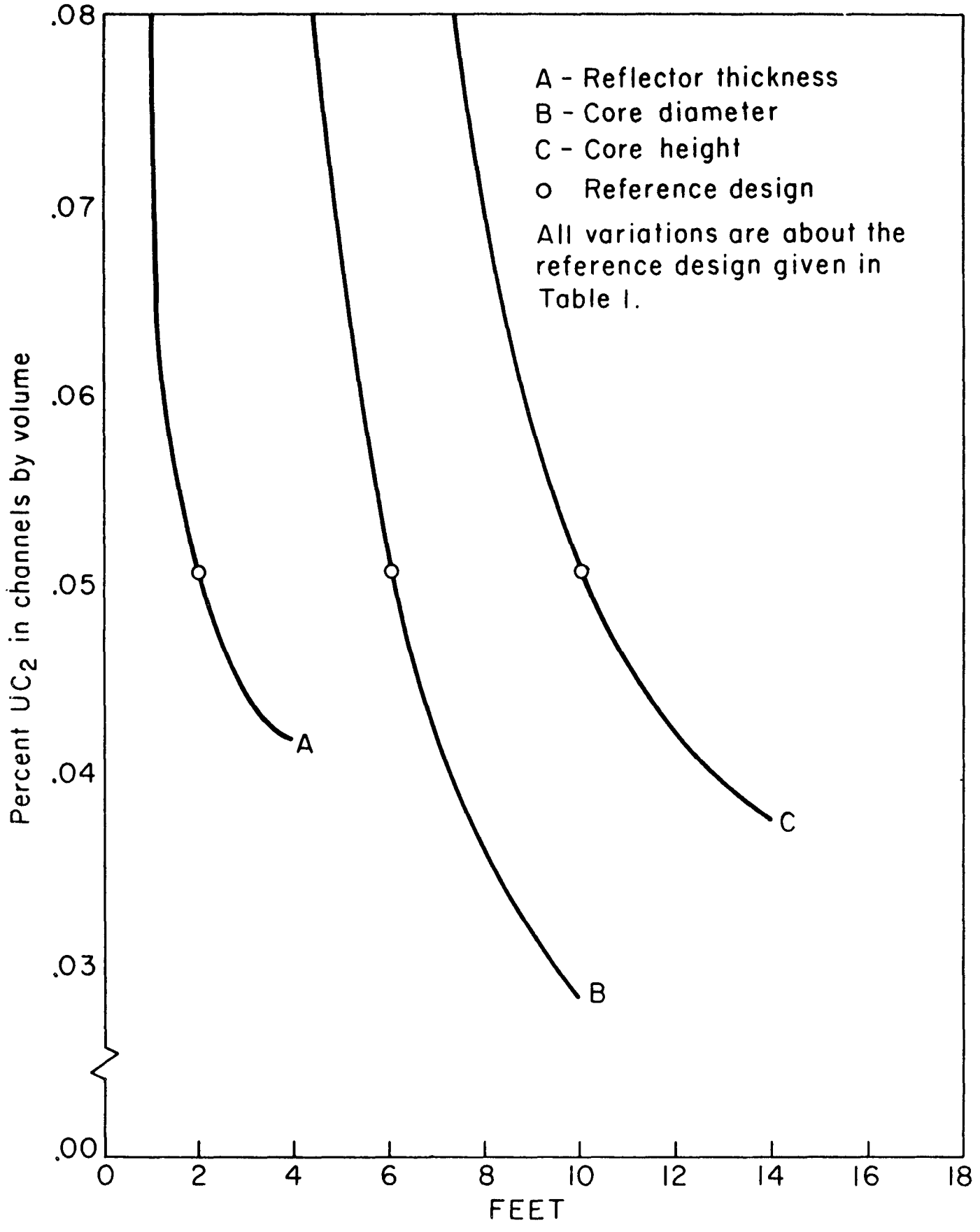

Fig. 4 Fuel concentration in channels versus reactor dimensions.

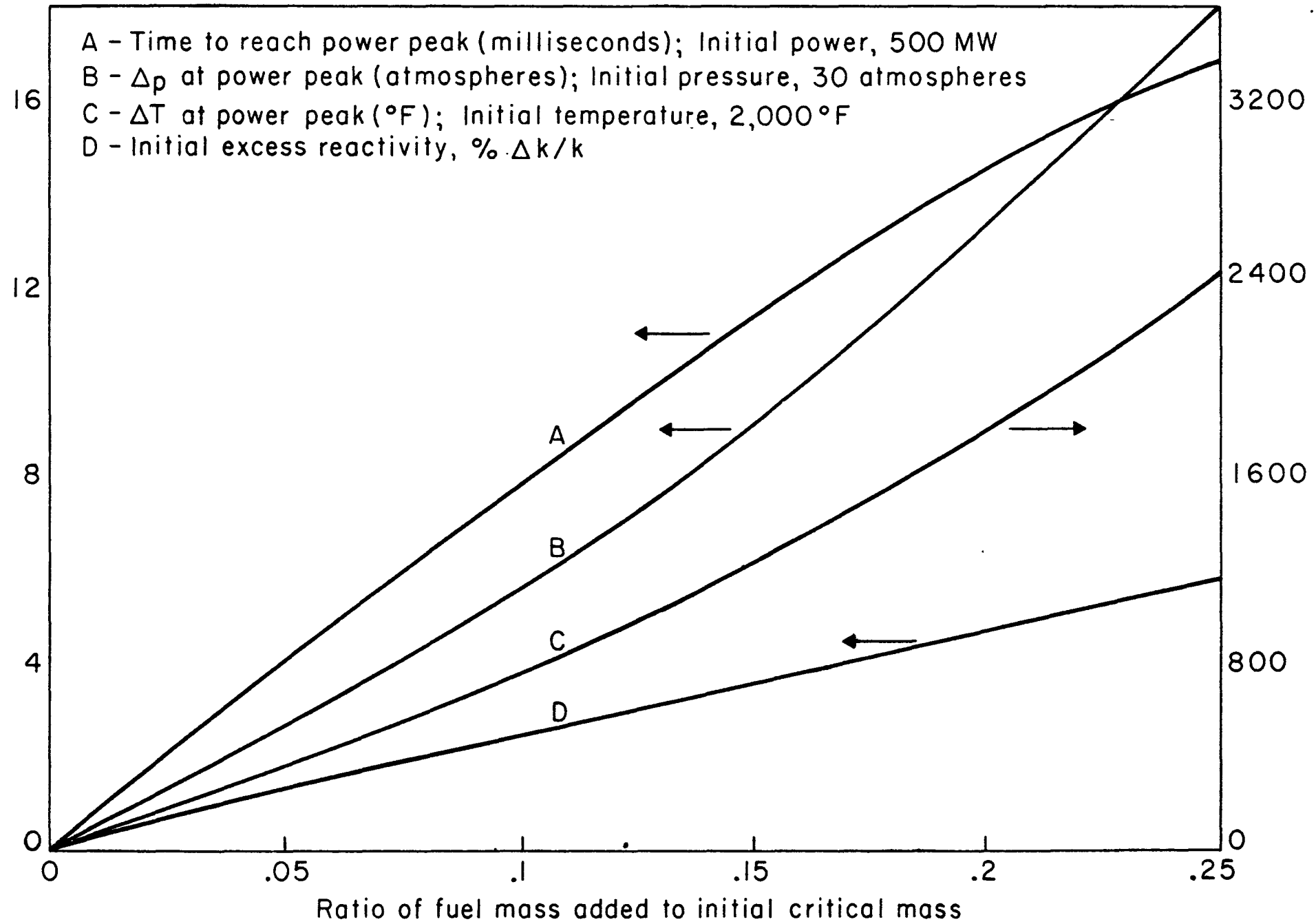

Fig. 5 Reactor conditions resulting from the instantaneous addition of excess fuel.

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