CONTENTS

APPENDIX C. THE ONION IFE REACTOR CONCEPT

C.1 BACKGROUND

The "Onion" reactor concept described below received about the same overall score as the Osiris concept that was chosen for further analysis. The Onion has a number of features that make it a viable candidate for future study.

C.2 GENERAL DESCRIPTION

To keep reactor costs reasonable and to accommodate heavy ion beam transport, the first wall must be placed close enough that some vaporization does occur. The Onion concept allows controlled vaporization of a very thin surface coating. As discussed below, this vapor very quickly recondenses on the wall with only 1-2 percent lost out the penetrations. This loss is periodically replaced by injecting fresh wall material into the chamber.

The vaporization process generates stress waves that propagate into the wall. Because the initial duration of these waves is so short, 1-3 nanoseconds, attenuation is very rapid. Furthermore, the wall material failure stress tends to be much higher under pulsed loading compared to static. The result of all this is that the wall is likely to survive such repeated pulses. There is a flowing liquid coolant in intimate contact with the wall. This coolant also serves as a mass loader to lower the kinetic energy delivered to the structure by the blowoff impulse, and as a stress wave coupler to carry the stress away from the first wall and dissipate it.

There are a number of issues that must be addressed with this concept such as the amount of material blown off and the time it takes to recondense on the wall. This determines the amount that is lost out the penetrations, mainly the beam lines, and the influences the choice of replacement technique. Another issue is the magnitude and duration of the stress waves generated by x-ray blowoff and the degree of attenuation during propagation. The kinetic energy delivered to the first wall/blanket also generate hoop stresses in this structure. Lastly, the compatibility of the coating with the target debris must be considered.

Carbon is an especially attractive coating because of its high sublimation point and low-Z, which limit the amount blown off, and low activity. There are others also worth considering such as tungsten, tantalum, aluminum, beryllium, lead, lithium lead, and Flibe.

In the following sections, we describe a conceptual design using carbon coating, a unique carbon/SiC composite first wall and blanket structure, and flowing liquid Flibe (Li_2BeF_4) coolant. We also examine a metal chamber with liquid lithium lead coolant. Clearly, there are other combinations that may work just as well or better, and these could be explored in the future. One interesting possibility, particularly for near-term reactors, is ferritic steel with Flibe because the low activity requirement is reduced due to activated indirect target debris. Flibe readily wets metals (it doesn't wet carbon), and is chemically compatible with ferritic steel[C-1] up to at least 600°C.

C.3 REFERENCE DESIGN

The conceptual design is sized for 3000 MW of fusion power, delivered with 300 MJ yield targets at 10 Hz. The neutron power is 2000 MW, with the remainder going to wall surface heating. The chamber is sized to be replaced once a year. We believe that the first wall material chosen, discussed below, can withstand an integrated neutron fluence[C-2] of $4 \cdot 10^{22}$ n/cm^2. With an 80% power factor and an estimated fivefold scattering of the incident fusion neutrons, the required first wall radius is 5.5 m for one year life. With this radius, the neutron wall loading is 5.3 MW/m^2 and the surface power is 2.6 MW/m^2. The surface energy dose per pulse is 0.26 MJ/m^2 (6.3 cal/cm^2) (there is considerable data available at these fluences from underground nuclear tests). The resulting reaction chamber size is small enough to be economical, yet not so compact that high heat fluxes would present engineering difficulties.

C.4 DESCRIPTION OF REFERENCE DESIGN

The reference design is depicted in Fig. C.1 (the "onion" refers to the layers of coolant paths). The first wall consists of a renewable carbon coating 20-50 μm thick on a Vapor Carbon Silicon (VCS) composite wall 0.8 cm thick. VCS is the proposed isotropic composite mentioned above. It consists of annealed vapor-grown carbon fibers in a chemically vapor-infiltrated silicon

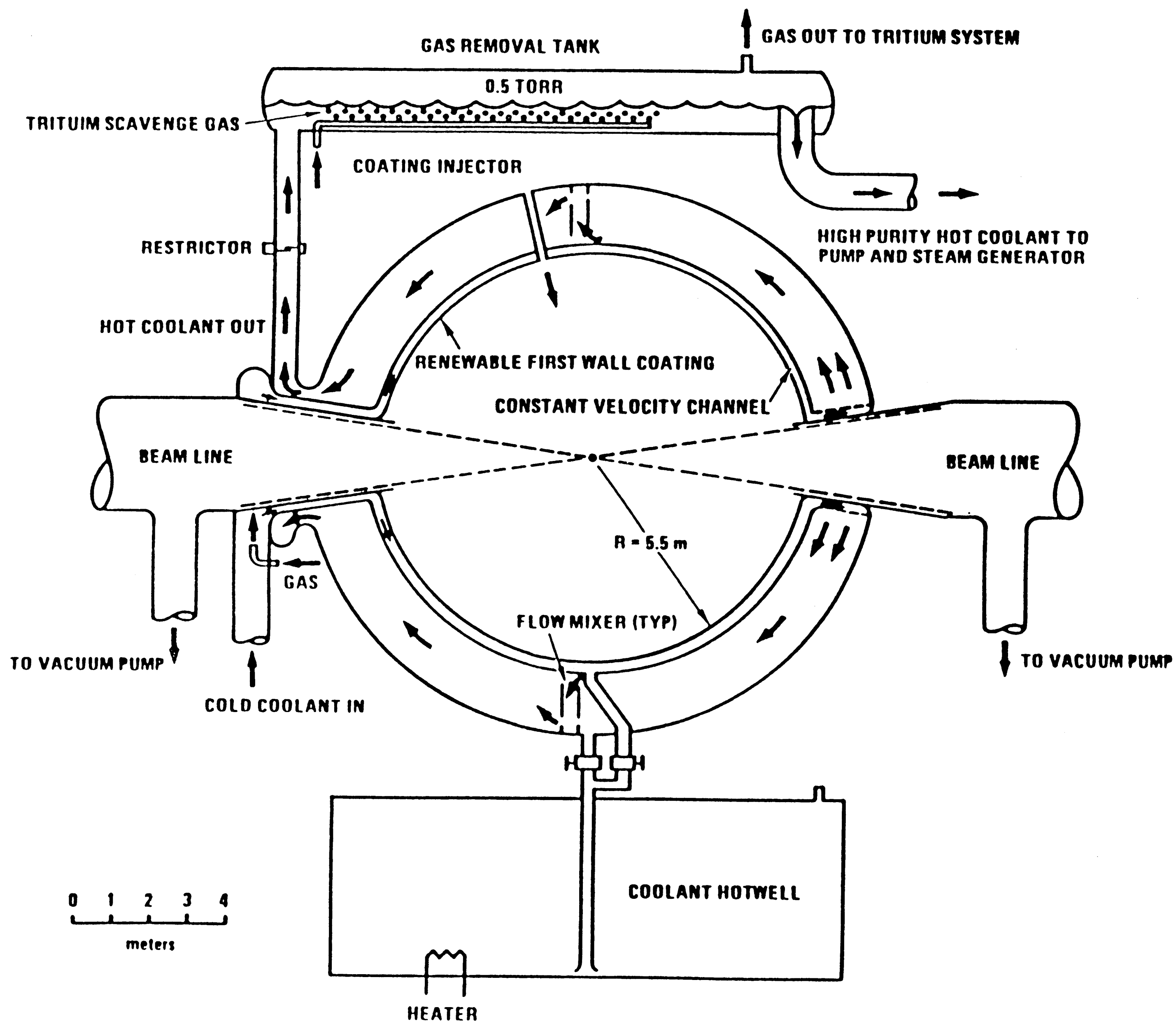

Fig. C.1. The Onion reactor reference design.

carbide matrix. The material has a thermal conductivity approaching copper, very high heat flux and high temperature capability, and neutron damage resistance. It is also resistant to tritium permeation and reducing atmospheres like hydrogen. This material is in the preliminary development stages at General Atomics.

The Flibe coolant removes the first wall heat, absorbs the neutron power, and provides tritium breeding. It makes two passes, one at high velocity along the backside of the first wall and slow return pass to collect the neutron heat. Gas bubbles can be injected in the Flibe in two places: first to dissipate stress waves and second to extract tritium and other gases. Note that the Flibe is reusable and is drained into a hotwell for the annual chamber replacements; only the empty chamber is replaced.

The next sections describe key features of the reference design in more detail.

C.5 RENEWABLE FIRST WALL COATING

We have used the CONRAD hydro code[C-3] to determine the depth of vaporization in the carbon surface layer and the resulting impulse and stress waves. Only about 0.5 μm (370 grams) of carbon are vaporized each shot. All vaporization is due to the soft x-rays, which make up 60 MJ of the fusion yield. The 30 MJ of ions and target debris arrive later and heat the expanding carbon vapor. A small amount of additional carbon is vaporized by radiation from this vapor.

Figure C.2 shows calculated recondensation of the vaporized carbon. Ninety percent of the carbon has recondensed in 3 milliseconds. Fully 99.7% is condensed in 10 msec. However, some 80 msec are needed to get the chamber density down to the level needed for heavy ion beam propagation[C-1] about $4 \cdot 10^{12}$ cm^{-3}. This is compatible with a 10 Hz repetition rate. It is half the interpulse time for the Osiris reference design. A simple pumping calculation shows that only about one percent of the carbon is lost out the beam lines so that only about four grams must be replaced each shot. There are many creative ways to introduce this carbon into the chamber. The one that we prefer at the moment is to mechanically inject carbon soot into the chamber away from the beam axis. This will be vaporized by the fusion energy and condensed on the wall. Subsequent shots will spread out this distribution if it is initially nonuniform.

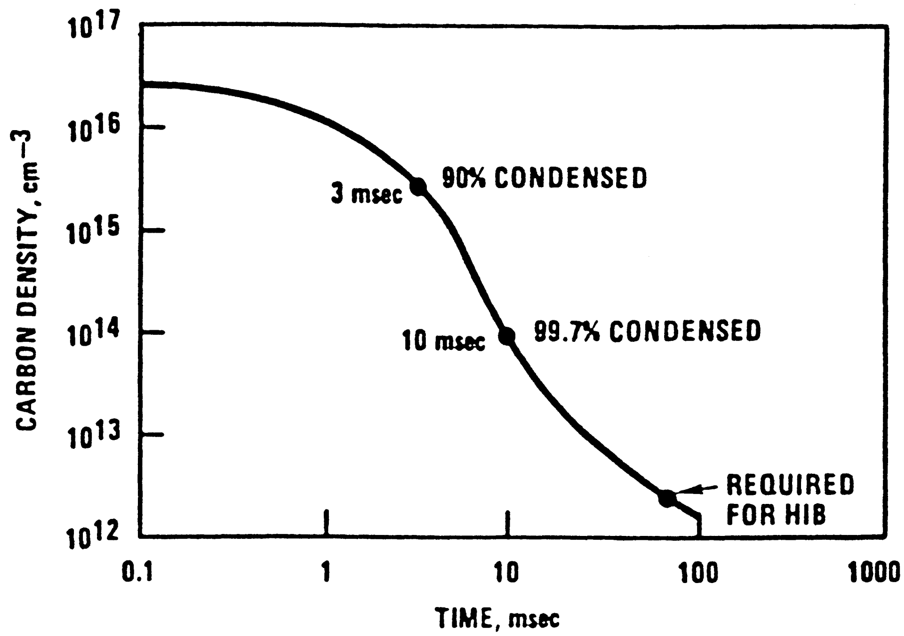

Fig. C.2. Recondensation of vaporized carbon.

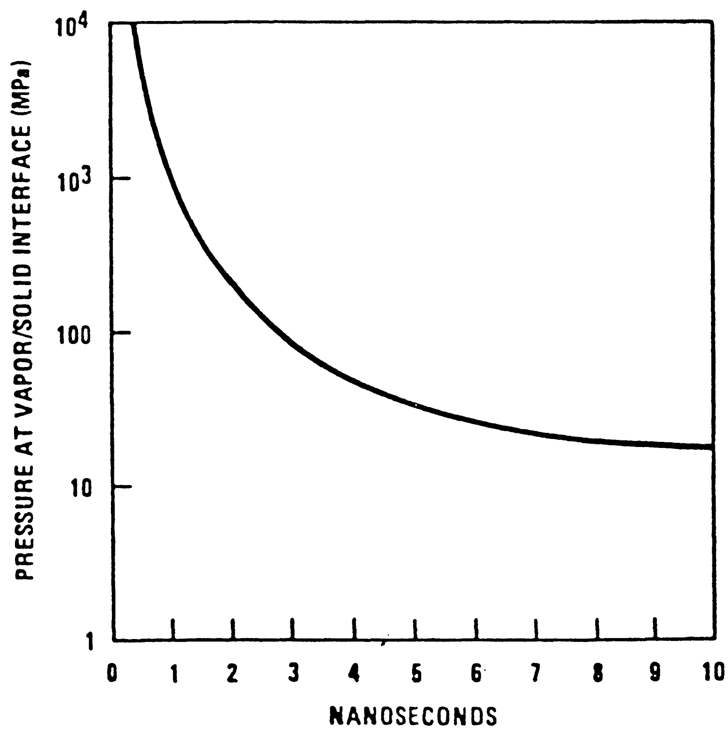

Fig. C.3. Pressure history at vapor/solid interface of carbon layer.

The CONRAD code also calculates the pressure at the vapor/solid interface, and this is shown in Fig. C.3. In one nanosecond, peak stress has fallen to about 1000 MPa; and it is about 200 MPa in 2 nsec. The latter is in the range of the static tensile strength of the carbon layer, and there is data from other materials that indicates the strength under such short-pulse dynamic loading could be as much as 10 times higher. Therefore, the carbon layer may survive because of the brief, nanosecond level duration of the stresses. Figure C.4 shows such data for aluminum.[C-4] Extrapolating back to nanosecond levels suggests a 10-fold increase in tensile strength over static levels.

There are other coating materials that we are also investigating. Aluminum or lead, for example, applied as liquids would not be subject to stress failure. And the higher atomic number would have greater soft x-ray stopping power, resulting in even shallower removal depths and shorter stress duration. Delivered impulse may be higher, however, than carbon. The activation of these materials is also a disadvantage. Lead is interesting because it can be applied from indirect target materials. This was exploited in a previous study[C-5] that could be considered a precursor to the Onion.

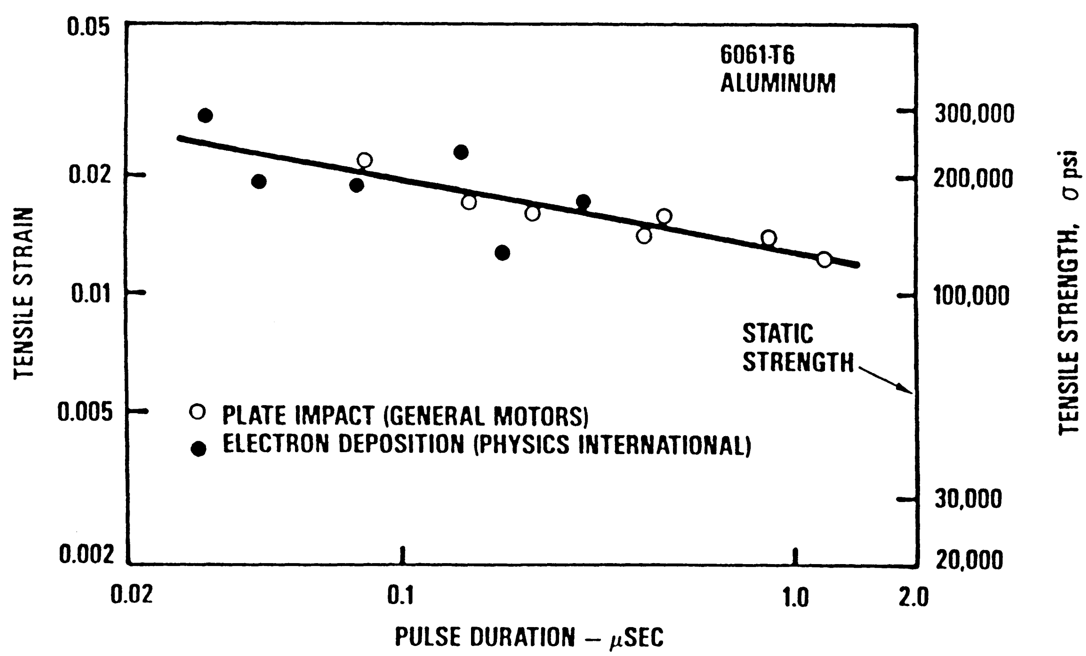

Fig. C.4. Influence of stress duration on tensile strength for aluminum.

C.6 FIRST WALL STRUCTURE

The first wall structure must be capable of high temperature operation, and high heat flux. It must be resistant to neutrons, have minimal tritium absorption, resist reducing atmospheres, and preferably be low activation. We expect the proposed VCS composite to meet these requirements. The composite uses isotropically oriented whiskers of vapor-grown carbon fibers[C-6] 0.5-1.0 mm long and 5-10 μm in diameter in a chemically vapor infiltrated silicon carbide matrix.[C-7] The SiC retards tritium permeation, a significant advantage over carbon-carbon composites. The annealed fibers have an axial thermal conductivity of nearly 2000 W/m-K at room temperature. Ignoring any contribution from the SiC, VCS with 50% carbon fibers randomly oriented should have a conductivity of 330 W/m-K at room temperature. Based on data for other carbons,[C-8] we estimate that VCS irradiated to $4 \cdot 10^{22}$ n/cm^2 would have a conductivity of 83 W/m-K at 1300K operating temperature, well above SiC-SiC composites.

With a low thermal expansion coefficient of about $4 \cdot 10^{-6}$/K, an elastic modulus about that of steel, and an expected tensile strength of 140 MPa, the allowable ΔT across the wall based of thermal stress is 270K. For the design heat flux of 2.6 MW/m^2, the allowable wall thickness is 0.8 cm. This is an acceptable thickness, and the shell should then be able to resist the other loads from the coolant and atmospheric pressure. It would have to reinforced with ribbing, however, to resist buckling. With the use of Flibe coolant, the first wall needs to seal against low pressure liquid leaks, not high pressure gas. Assembly can therefore be with tongue-and-groove panels, perhaps with a silicon sealer.

C.7 FLIBE BLANKET

While Flibe is a poor heat conductor, its low viscosity makes it a tolerable heat *convector*. It works well in this case because of the high temperature capability of the first wall permits high boundary layer ΔT's. The Flibe makes its first pass at a constant 6 m/sec velocity to remove the first wall heating. The Reynolds number is 11,400 and the heat transfer coefficient is an acceptable 12,200 W/m^2-K. The required film temperature rise is 216 K. The maximum VCS temperature is then about 1190 K, well within the capability of the material.

The total residence time of the Flibe in the blanket is about 100 sec during which about 0.5 grams of tritium are bred. The Flibe also dissociates to TF and F_2 during tritium formation, which react with silicon and carbon. To mitigate this, we would add micron-sized silicon and carbon powder to the Flibe to act as scavengers. The resulting SiF_4 and CF_4 are gaseous and could be removed with the tritium gas in the separator tank shown in Fig. C.1.

The flow pressure drops are 0.35 MPa for friction plus 8 kPa for turning. Flibe pumping power for the reactor chamber is then a reasonable 1.5 MW. The maximum Flibe pressure in the chamber is only 0.5 MPa. At $40/kg[C-9] the estimated cost of the Flibe is a reasonable $50 million.

C.8 BLOWOFF IMPULSE AND CHAMBER RESPONSE

The vaporization of the carbon gives a blowoff impulse of I = 8 Pa-sec. The resulting kinetic energy E and velocity u of the structure is given by

$$E = \frac{I^2}{2\,\rho\,t}, \qquad u = \frac{I}{\rho\,t}$$

where ρ and t are the bulk density and thickness of the structure. These equations show why thin, unsupported plates can present problems when there is wall vaporization (At very small t, of course, I drops off because the wall begins moving almost immediately). If the 8 mm VCS wall were not backed by Flibe in intimate contact, it would move away at 0.5 m/s. Because of the Flibe, this is reduced to a negligible 0.005 m/s. The kinetic energy is also reduced, from 2 J/m^2 to 0.02. This energy must be absorbed as hoop strain in the structure. Clearly, this is easier in the latter case.

C.9 COMPATIBILITY WITH INDIRECT TARGET SHELL MATERIALS

While indirect drive targets eliminate the need for uniform illumination, they require high-Z shells around the target to absorb and reradiate x-rays. This material ionizes and is driven to the wall at very high velocity. It interacts with the blowoff vapor, recombines, and condenses and/or reacts chemically with the blowoff.

Many high-Z materials can form carbides with the blowoff carbon. This will complicate recycling because they will plate out on the wall. Carbon may therefore not be the best coating. Ideally, the coating and target material should be the same. Possibilities are tantalum, tungsten, mercury (cryogenic targets), lead, and lithium-lead (especially if this is the blanket material). A molten coating like mercury or lead could be recycled by draining, and is self-healing. However, vapor density limits in the chamber may limit temperatures to unacceptably low levels in some cases.

C.10 ALTERNATE ONION WITH METAL CHAMBER AND LITHIUM-LEAD

We briefly looked at another version of the Onion, shown in Fig. C.5, that has vanadium alloy metal walls and flowing lithium lead coolant. Here the LiPb would serve as the first-wall coating, making the structure very leak-tolerant. The coating would stay liquid and be continuously drained. The blanket inventory could also be used to make the target shells.

Vapor pressure requirements for beam propagation will limit peak coating temperature to ≤600°C. The chamber is therefore larger than the previous case, with R = 6 m, and the wall heat flux is 1.66 MW/m^2. The alloy used is V-15Cr-5Ti, which is a candidate fusion reactor material.[C-9] Thermal stress limits the first wall ΔT to about 170°C, corresponding to a 3 mm wall thickness at this heat flux. This can be built up from welded sections as shown in the figure, with all of the welds hidden from the primary neutrons.

Power conversion issues like pinch point limit the minimum LiPb inlet temperature to above 365°C. The LiPb film drop is 5°C. To keep the coating temperature to 600°C, the bulk LiPb temperature exiting the first wall region is about 425°C. Fusion power energy partitioning them sets the LiPb outlet temperature to 515°C. While this is too low for a conventional steam cycle, it can serve a 400°C multireheat steam cycle, which can deliver 41.5% efficiency. This is not much less than the 45% achieved in conventional steam cycles. This low temperature cycle would have supercritical steam and three reheats. While this requires a lot of steam ducting, costs should not be an issue because the lower temperature permits the use of lower cost materials.

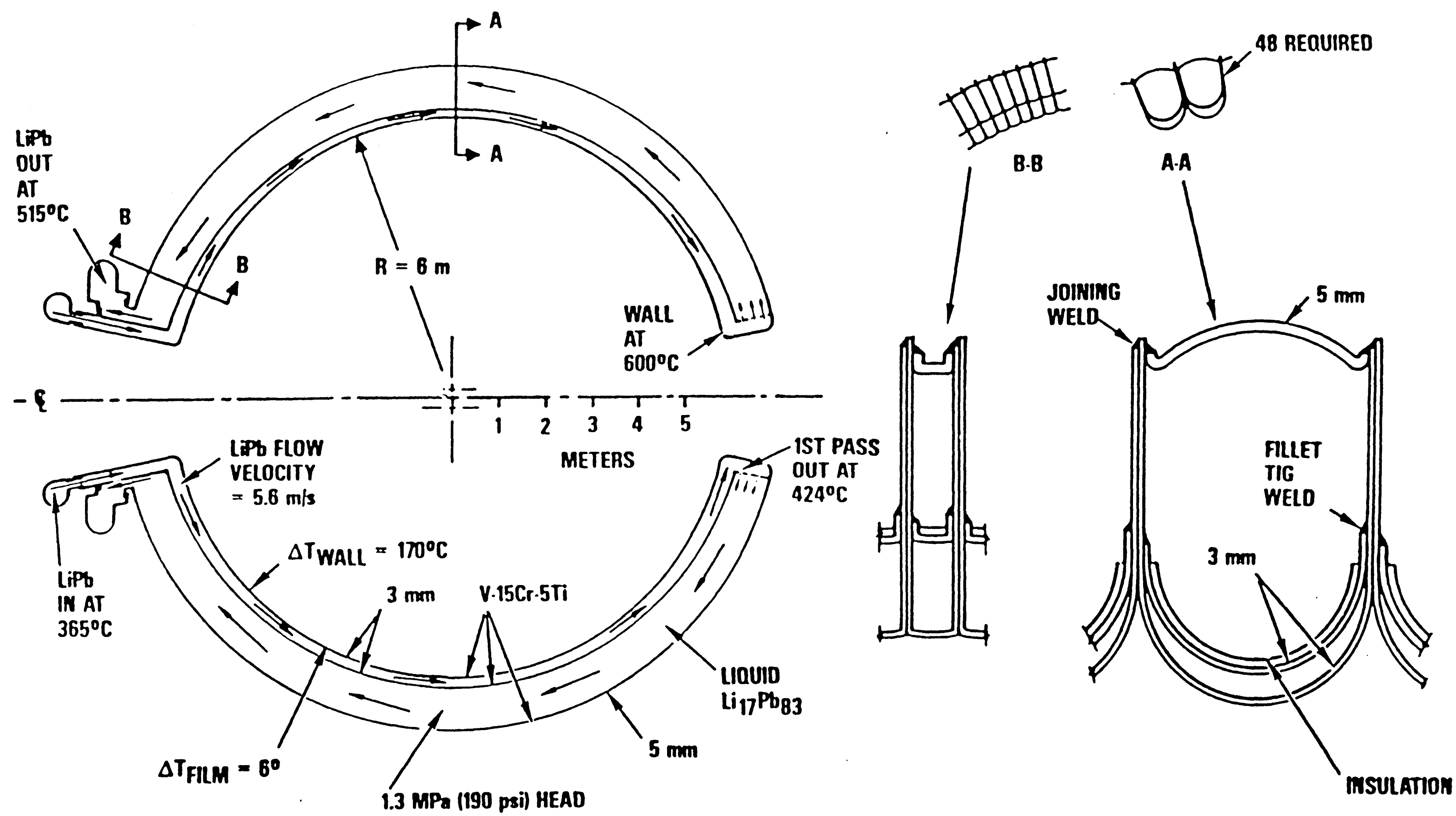

Fig. C.5. Alternative, all-metal version with lithium-lead coolant.

C.11 MODIFICATIONS FOR LASER DRIVER

The Onion reactor concept above is easily modified for laser drivers. Then the first wall vaporization from soft x-rays is eliminated by introducing a 0.5-1.0 torr xenon gas into the chamber, an acceptable level for laser beam propagation.[C.1] Vaporization from harder x-rays that get through the gas is eliminated by retaining the low-Z first wall, which spreads out the energy deposition. The uniformly-distributed beam ports can pass directly through the Flibe blanket. They would be shaped with leading and trailing edges so as to eliminate Flibe stagnation, and vacuum pumping could be done through these ports.

C.12 SUMMARY

The Onion reactor concept with a renewable carbon coating, a carbon fiber/SiC first wall, and a flowing Flibe blanket appears to be a robust, low activation design. Technology development requirements are not unreasonable. Work needs to be done in characterizing stress wave propagation and damage, particularly under repeated pulses. The VCS composite needs to fabricated in large sections and tested. And concepts such as scavenging powders to mitigate Flibe chemistry need to be examined in more detail. Other combinations, such as metal chambers with Flibe or lithium-lead, need further investigation.

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