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Thermal control of the liquid lithium divertor for NSTX

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ABSTRACT

The liquid lithium divertor (LLD) to be installed in NSTX has four toroidal panels, each a conical section inclined at 22° like the previous graphite divertor tiles. Each LLD panel is a copper plate clad with ~0.25 mm of stainless steel (SS) and a surface layer of flame sprayed molybdenum (Mo) that will host lithium deposited from an evaporator. LITER (evaporators) already used in NSTX will be upgraded for the LLD. Each has twelve 500 W cartridge heaters with thermocouples, 16 other thermocouples, and a channel for helium cooling. During LLD experiments, the LLD will be heated so that the lithium is just above its melting temperature. The length of each shot will be preset to prevent excessive evaporation of lithium from the LLD. This duration depends on the heat load and is likely to be in the range of less than a second to several seconds. Careful thermal control of the LLD is important to maximize the shot times and to guide operation of the LLD. This paper describes the layout of the LLD, its expected thermal performance, the control system, and supporting experiments and analysis. A companion paper in this conference, "Physics design requirements for the national spherical torus experiment liquid lithium divertor," provides other information.

1. Introduction

The liquid lithium divertor (LLD) to be installed in 2009 in NSTX (National Spherical Torus Experiment) will provide a liquid lithium surface that the scrape-off layer of the plasma or, for shorter durations, the strike point of a single null plasma will contact. The objective is to observe the plasma when liquid lithium exerts strong pumping to reduce particle recycling. A companion paper explains further [1].

A lithium pellet injector and a lithium droplet injector ("DOLLOP") developed in the 1990s were important for the TFTR (Tokamak Fusion Test Reactor) "super-shots" and its D-T plasma program [2,3]. Subsequently, lithium plasma facing components were used in several other fusion experiments [4–9]. In H-mode divertor discharges in NSTX, experiments with lithium pellet injection and a lithium evaporator have demonstrated for the first time the benefits of lithium in reducing hydrogen recycling, lowering the impurity content, and improving confinement [9–11].

The NSTX Team at the Princeton Plasma Physics Laboratory (PPPL) and Sandia National Laboratories have undertaken the preparation of the LLD as a collaboration funded by a 3-year NSTX Laboratory grant from the US Department of Energy. Both partners have developed the design of the LLD. Sandia is procuring the divertor plates for the LLD, the thermal control system and rack, and supporting thermal analysis and testing. PPPL is providing the detailed drawings, hardware to secure the LLD to the NSTX divertor rails, the new carbon tiles that are necessary to fit the LLD as well as the cabling, planning, and labor for installation.

In addition to the references noted above that deal primarily with the impact of lithium on plasmas, there has also been important experience gained in the technology of supplying liquid lithium surfaces for use in fusion experiments. The US at one time pursued fusion reactor design studies and related materials development with lithium and vanadium system [12,13]. More recently, research in the ALPS and APEX Programs [14–17] has included work with a flowing lithium system at Sandia [18,19], and coordinated research for the CDX-U device at PPPL used laboratory facilities at UCSD (University of California, San Diego) and lithium injectors developed by UCSD [18]. These were initially considered as the delivery system for the LLD, but this approach was abandoned due primarily to the requirements for further development and the port access needed on NSTX. Also, R&D in Europe and especially in Russia has included the development of designs and hardware for flowing lithium

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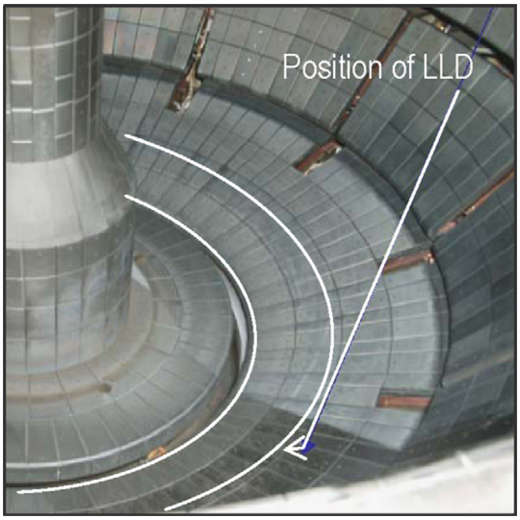

Fig. 1. Photo of NSTX divertor with future location of LLD indicated by white lines.

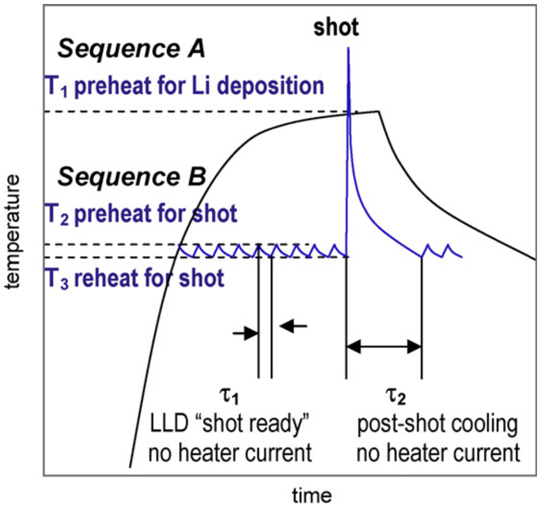

Fig. 2. Sketch showing heat up phase and thermal cycling of heaters.

systems [20] and for capillary systems in which lithium covers and continually resupplies a metal mesh. This idea was used in the lithium limiter deployed in the Frascati tokamak [6,7] and is the basis of a design advanced by Sandia for a Phase II LLD discussed later under future work.

2. Layout and operation of the LLD

The LLD has four toroidal panels, each a conical section inclined at 21.5° like the previous graphite divertor tiles and subtends and angle of 82.5°. Fig. 1 shows the position of the LLD in NSTX. The inner

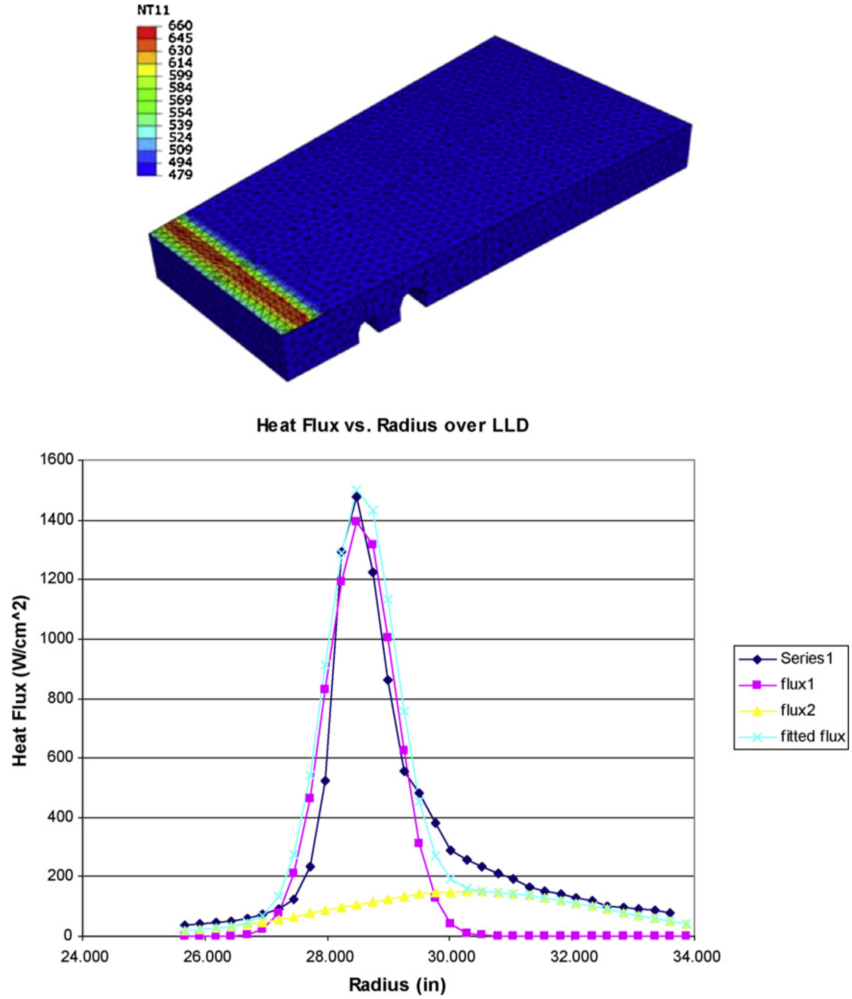

Fig. 3. (a) Reference strike point profile for NSTX shot with a peak heat load of 14 MW/m^2 and (b) calculated 2D temperature profile across the LLD for similar profile shape and peak heat load of 2 MW/m^2.

edge of the LLD is at a radius of 655 mm. Each panel is a copper plate 215 mm wide and 22.2 mm thick clad with ∼0.4 mm of stainless steel (SS) and a surface layer of flame sprayed molybdenum (Mo) that will host lithium deposited from an evaporator. LITER (evaporators) already used in NSTX will be upgraded for use with the LLD. Each panel has the following features:

- 12 cartridge heaters (500 W) with embedded thermocouples;
- 12 control thermocouples near the heaters;
- 4 other thermocouples;
- channel with brazed SS tube for helium cooling between shots;
- center support stalk;
- electrically insulated pivoting tethers near corners to restrain motion of the LLD from $J \times B$ forces (A similar tether has been used effectively in JET.).

During experiments using the LLD ("LLD shots"), radiation and helium cooling will cool the LLD between shots. Then, the LLD heater control system will arrest the cooling and adjust the LLD to a preset range in temperature for the next shot. More specifically, the heaters will go into a holding pattern (Fig. 2) between two trip points in the thermal control system much like a household thermostat, but with a "zero cross" option that switches power on at the time during the current cycle when there is zero voltage. The timing sequence for each shot begins with a signal that the neutral beams are ready at ∼2 min before the shot. The heaters must be shut off before the magnets are energized on to eliminate $J \times B$ (electromagnetic) forces on the LLD and on the heater cables. The upper set point for the LLD heaters keeps the liquid lithium far enough above its melting temperature (181 °C) to avoid freezing in the interim after the heaters turn off before the shot. We will monitor the LLD using its thermocouples and IR cameras that can view about 2/3 of the LLD at one time.

A fundamental issue in operating the LLD is to maximize the shot time while avoiding excessive evaporation of lithium. During a shot, thermal diffusion into the Li/Mo/SS/Cu layers is limited and the helium cooling is negligible. Evaporation of lithium increases exponentially with temperature and will limit the duration of a shot. We do not have a "lithium trigger" to terminate a shot before significant evaporation occurs, so we must preset the duration of each shot based on experience gained as we operate the LLD with various plasmas plus an extensive suite of cases from thermal analyses that gives us the expected thermal performance of the LLD for various heating profiles.

3. Analysis and testing

Co-author Zakharov previously evaluated the thermal limits for many combinations and thicknesses of materials and two scrape-off layer (SOL) profiles [21]. Our objective in further analyzing the thermal performance of the LLD is to develop a suite of 3D modeling results that describe the expected distribution on an LLD plate. The cases include LLD shots with the strike point in various positions, e.g., (1) stationary on the LLD, (2) swept across the LLD, (3) on row of narrow carbon tiles just inboard of the LLD, and (4) on carbon tiles just outboard of the LLD, if this is possible. In Cases 3 and 4, the LLD will pump the outer SOL or the private flux region, respectively, and will permit longer shot times, since the strike point is not on the LLD.

Fig. 3a shows the strike point profile for an NSTX with the strike point on the outer limiter. We use this for our modeling of a similar case with the LLD (Fig. 3b) and for our initial modeling of strike point sweeping. For sweeping, the "wings" of the profile are particularly important since the time-integrated heating includes the wing portion before the strike point arrives.

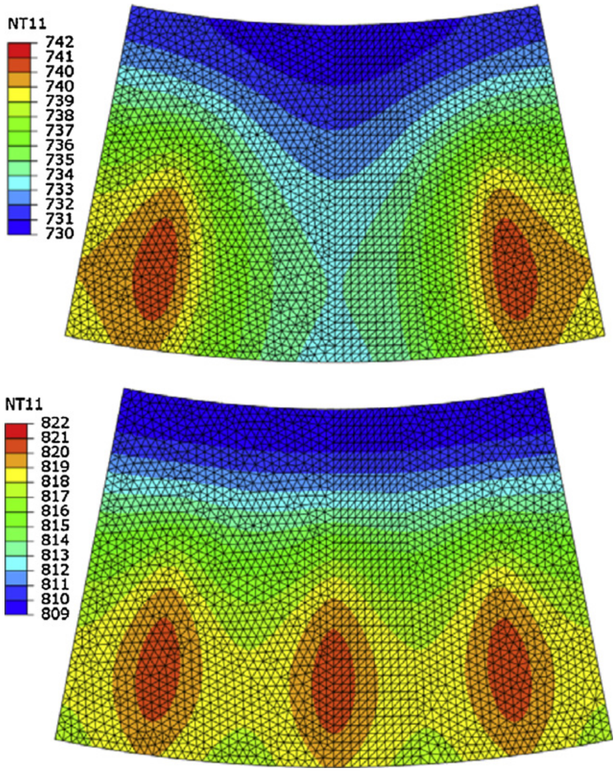

Fig. 4. (a) Thermal modeling results for cases with LLD 1/4 plate mockup (photo); (b) in lower case middle heater is not operating.

There are also various physical variations of interest, e.g., startup with a frozen limiter, purposeful overheating to dissolve surface contamination, local hot spots and cold spots, and cases with failed heater(s). Cold spots with solidified lithium will reduce pumping but are not a problem otherwise. We also analyzed cases for various sizes of braze flaws between the SS layer and the Cu plate, both as a guide in quality assurance in building the LLD and to characterize the effects of joining flaws during operation of the LLD.

Benchmark heating tests of a copper plate mockup with three heaters provided baseline data for our thermal modeling as well as the load for our shakedown testing of the control rack, briefly described later. Fig. 4a shows a thermal analysis of the mockup with one heater off, and Fig. 4b shows a colorized IR image of the corresponding test with the mockup in which shows the same distribution of temperature as the model.

Lithium wetting tests were performed at PPPL and Sandia, but are not reported here due to limitations in space.

4. LLD control rack

We will control and monitor the LLD during its operation and archive the data, except for the IR data, which is tracked separately. For example, Fig. 2 shows modeling of the initial rise in temperature over ∼25 min during a morning startup with the heaters at 200 W followed by a series of thermal cycles. The repeated cycling is a holding pattern until the actual start of a shot. During each cool down steps of duration τ_2, the output from the control rack will give operators an average temperature for each quadrant of the LLD as well as some kind of "green light" signal confirming that the LLD is within its control range. When the heaters are again turned on to reheat the LLD, the status would be "red" (no shot).

Sandia will provide the control rack for the LLD supplied from a 208 V buss. The main components are: power conditioning and isolation switches for the two hot 208 V lines, heater controller and

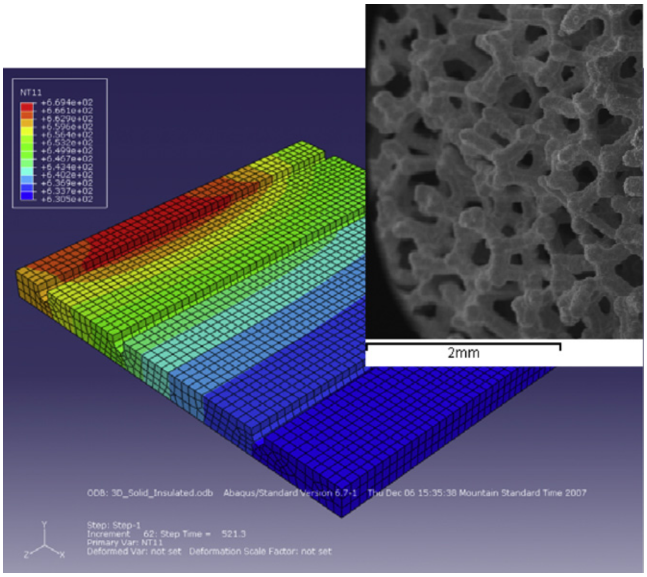

Fig. 5. Thermal modeling results for Mo mesh mockup without lithium heated at one end. Insert shows SEM photo of mesh.

switches for 48 heaters, data acquisition modules for 112 thermocouples, flow control switches and pressure monitoring for the four LLD cooling lines plus a programmable logic controller, and laptop computer for local control and data management. Only a summary description is given here due to space limitations.

5. Future work and conclusions

Sandia will be developing ideas and will perform some testing of mockups with a helium heat transfer system for heating and cooling of a liquid lithium divertor for a future application such as the proposed NHTX. Sandia had tested refractory helium-cooled heat sinks built by Ultramet with an integrally bonded internal open porous mesh that very effectively enhances heat transfer. These have demonstrated outstanding heat transfer [22]. We initially proposed a design for the LLD based on a porous molybdenum (Mo) mesh with the added specification that the Mo be deposited over a pyrolyzed carbon skeleton. The objective was to improve the thermal conductance of the mesh material by using high conductivity carbon with a coating of Mo. The mesh also provides a reservoir of lithium that would move to the surface by capillary action as evaporation depleted the surface layer of lithium.

We had started testing samples of such a mesh made by Ultramet, Inc. but postponed further work. Fig. 5 shows modeling for an initial thermal test with a heater at one end of the mesh and no lithium. The objective was to extract estimates of the average thermal conductivity of the mesh from measurements of the temperatures of the thermocouples in the mesh as heat propagation from one end of the mesh to the other. We have not yet processed these data.

As part of the NSTX Team, Sandia will work in the coming year to develop a concept for an LLD upgrade. Among its likely features are a lithium reservoir and more aggressive cooling.

The LLD fits into the existing divertor configuration with replacement of three rows of existing divertor tiles. We believe the design of the LLD and its system for thermal management are adequate for successful performance of LLD experiments in 2009.

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