TPOP-II: Tritium Fueling at a R
Scale

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ABSTRACT

As part of the International Thermonuclear Experimental Reactor (ITER
development program, Oak Ridge National Laboratory (ORNL) has fabr
injection system to test the mechanical and thermal properties of extrude
repeating single-stage pneumatic pellet injector, called the Tritium-Proof
Phase II (TPOP-II) Pellet Injector, has a piston-driven mechanical extruc
designed to extrude and accelerate hydrogenic pellets sized for the ITER
and D-T pellets have been produced in experiments at the Los Alamos N
Laboratory Tritium Systems Test Assembly (TSTA). About 38 g of tritiu
utilized in the experiment. Two types of runs were made: those in which
only extruded and those in which pellets were produced and accelerated
propellant. These extrusion experiments indicate that both T_2 and D-T w
extrusion forces than D_2 by about a factor of two and that the flow of the
characterized by static and dynamic shear strengths. This paper presents
TPOP-II extrusion experiments.

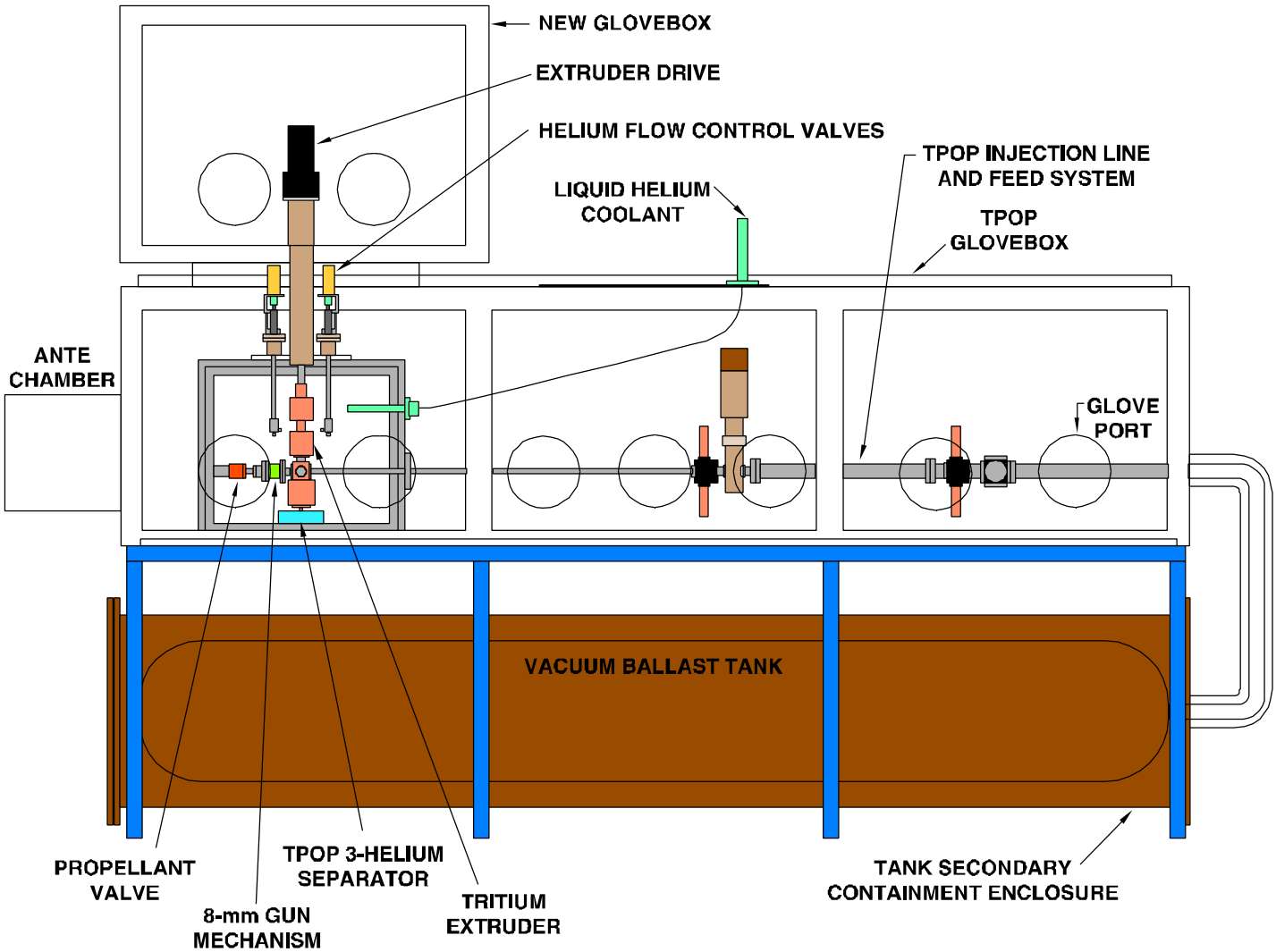
INTRODUCTION

The ITER fueling system[1] consists of both gas puffing and high-s
hydrogen pellets. Fueling rates for pellets have been set at 100 Pa
D_2, and D-T and 50 Pa-m^3/s for T_2. To achieve these rates, up to 1
pellets at about 1 Hz have been proposed. Pellets of this size wou
about a 10% perturbation in the plasma density if the entire mass
the core. Plasma fueling is important to the ITER overall operatin
because it can replenish burned-up fuel in the plasma, control pla
burn rate, establish a flow of hydrogenic ions to the scrape-off lay
impurities and helium ash concentrations in the core of the plasma
gas composition in the plasma edge. This latter point is important
opment of the concept of isotopic fueling.[2] In this concept, pellets
concentration would be delivered beyond the scrape-off layer for
fueling, and gas of high-deuterium concentration would be delive
scrape-off layer to control the density and composition of the dive
The high concentration of deuterium next to the wall would transl
tritium concentration in the wall and would significantly reduce (
tium inventory in the wall, which otherwise could approach sever
Therefore, pellets with a broad range of tritium concentration are
evaluated in these experiments.

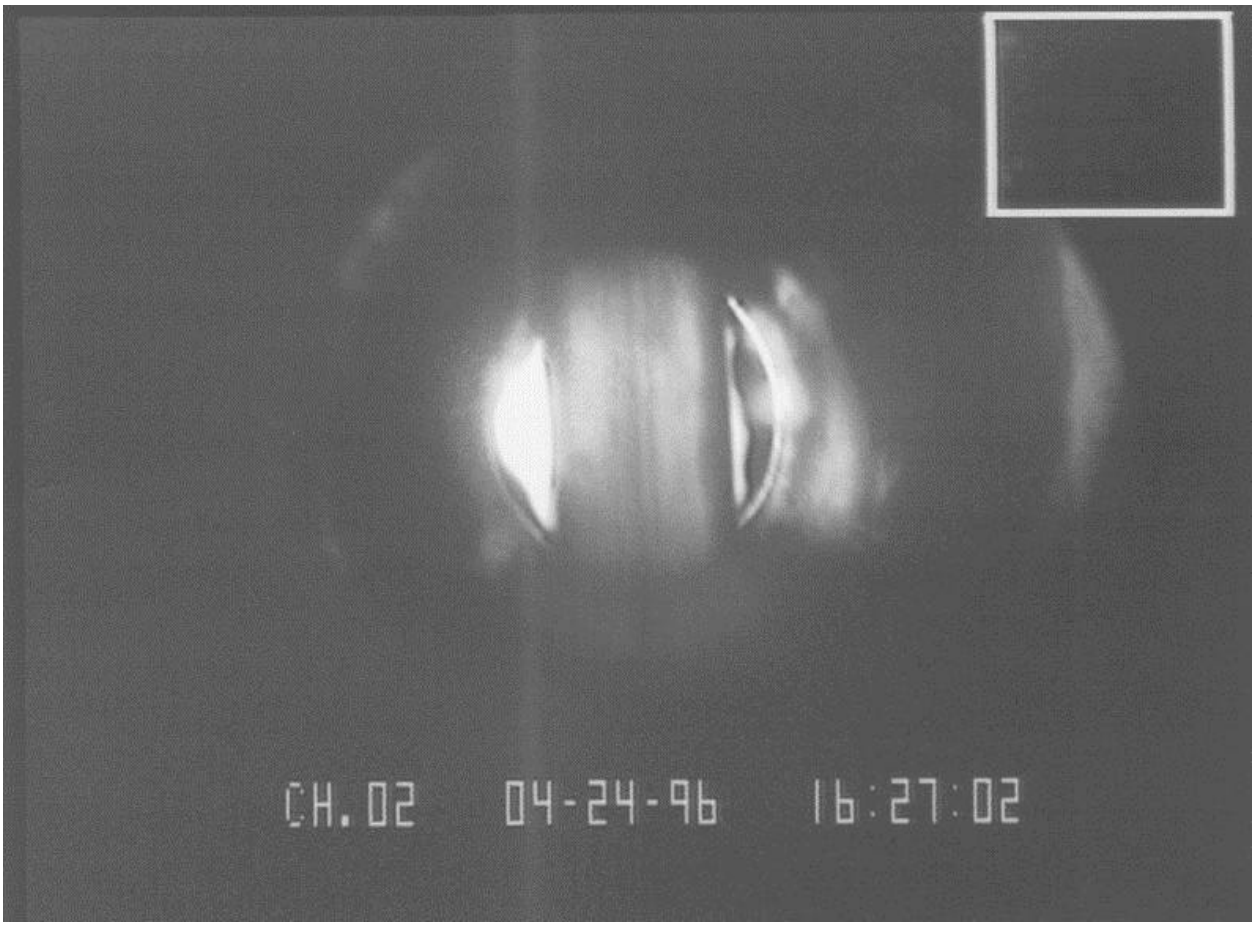
ORNL installed and operated two tritium pellet experiments in TS
established the basic scientific feasibility of production and pneur
acceleration of tritium pellets for fueling future fusion reactors. T
experiment, Tritium-Proof-of-Principle (TPOP), used a single-sta
gun in which a single 4-mm-diam pellet was frozen in-situ in the b
accelerated with high-pressure hydrogen gas. These experiments c
tritium and D-T pellets could be formed and accelerated to high s
produced some preliminary estimates of the strength of solid tritiu
II of this experiment,[7,8] the pipe gun has been replaced with a repe
matic pellet injector, which was developed by Combs, Milora, and
ORNL.[9] The specific embodiment of this gun is similar to the des
injector used on the Joint European Torus[10,11] and recently installe
tokamak experiment at General Atomic.[12] These extruder-based g
used to fuel fusion experiments with deuterium and hydrogen pell
ranging from 1.8-mm-diam at 10 Hz to 6-mm-diam at 1 Hz. The e
technique is quite general and has also been used in centrifugal pe
tors.[1,13] The Tritium-Proof-of-Principle Phase II (TPOP-II) gun is
produce nominal 8-mm-diam pellets as prototypes for those that v
fuel ITER. Unlike TPOP, which was a single-shot device, the new

produce streams of more than ten pellets at frequencies up to 1 Hz
run requires as much as 40 kCi (~4 g) of tritium for a single fill of

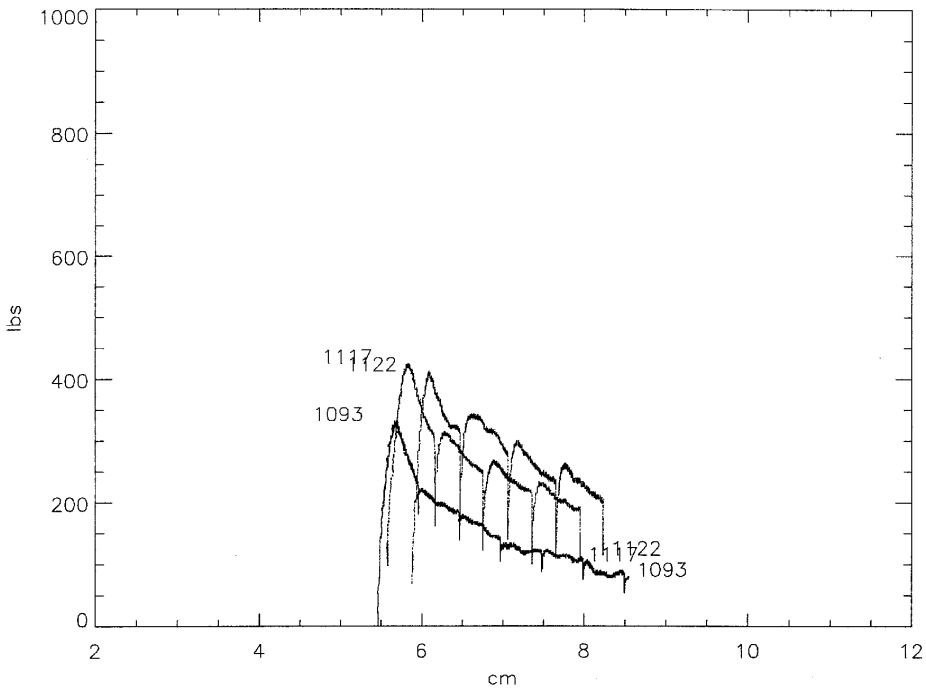
In tests of TPOP-II with deuterium feed at ORNL, up to 13 pellets
have been extruded at rates up to 1 Hz and accelerated to speeds o
km/s, using hydrogen propellant gas at a supply pressure of 65 bar
deuterium pellets 7.5 mm in diameter and 11 mm in length were p
largest cryogenic pellets produced by the fusion program to date.[7]
represent about a 10% density perturbation to ITER. Subsequently
nozzle was modified to produce pellets that are almost 7.5-mm rig
cylinders. Tritium and D-T pellets have been produced in experim
About 38 g of tritium have been utilized in the experiment. The tr
received in eight batches, six from product containers and two dir
TSTA Isotope Separation System (ISS). Two types of runs were m
which the material was only extruded and those in which pellets w
and fired with deuterium propellant. A total of 36 pure tritium run
mixture runs were made. These extrusion experiments indicate tha
D-T will require higher extrusion forces than D_2 by about a factor
that the flow of the material may be characterized by static and dy
strengths. This paper presents results of the TPOP-II extrusion ex

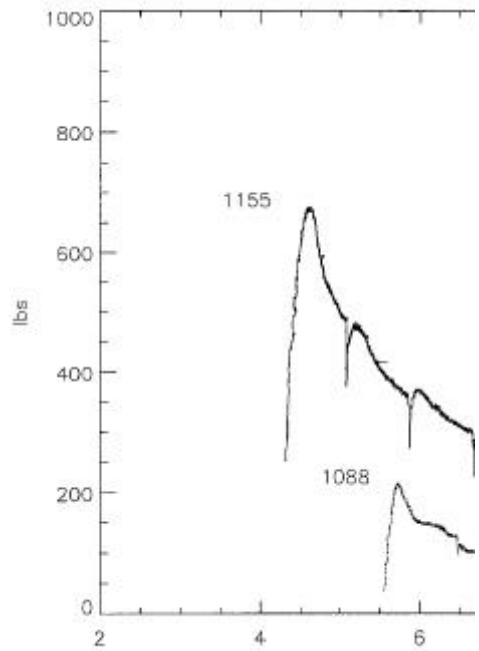


Layout of the TPOP-II experiment as it is installed at TSTA. The tritium extruder, extruder drive, 8-mm gun mechanism, and propellant valve are based on the RPI gun design. The mechanism is housed in a guard vacuum enclosure that provides a vacuum environment for thermal insulation of the cryogenic systems. A cryogenic ^{3}He separator is also housed in this enclosure. Liquid helium coolant is supplied from portable dewars to the glovebox, and coolant exhaust gas is exhausted from the glovebox to the stack at TSTA. Extruder cryostat temperatures are controlled by controlling the flow rate of coolant to the various cryostats using flow control valves and by feedback temperature control to heating elements attached to the individual cryostats. The extruder has both position and force elements attached to the ram and there is a window in the lower cryostat through which the quality of the extrusion can be observed and photographed. Shown below the glovebox is a secondarily contained, 600-L tank used to collect extruder exhaust gas for recycle. The system has its own valving manifolds and pumping system to control the flow to gas to and from the extruder.



Typical extrusion pure T_2 in mid run. The quality of the extrusion, as indicated by the transparency of the extrusion, is best in the middle of the run. The extrusion is 5.5 mm wide and 9.5 mm thick (i.e., into the page). Fresh transparent extrusions darken (become translucent then opaque) after several tens of seconds presumably due to beta decay. Apparently the pressure in the extruder is high enough to heal these imperfections during at least part of the extrusion process because some transparent material is produced. However, darkness observed in other parts of the extrusion could either be due to residual beta-decay imperfections, which have not been healed, or to more gross mechanical imperfections such as cracks and holes, which presumably would take more pressure to heal.

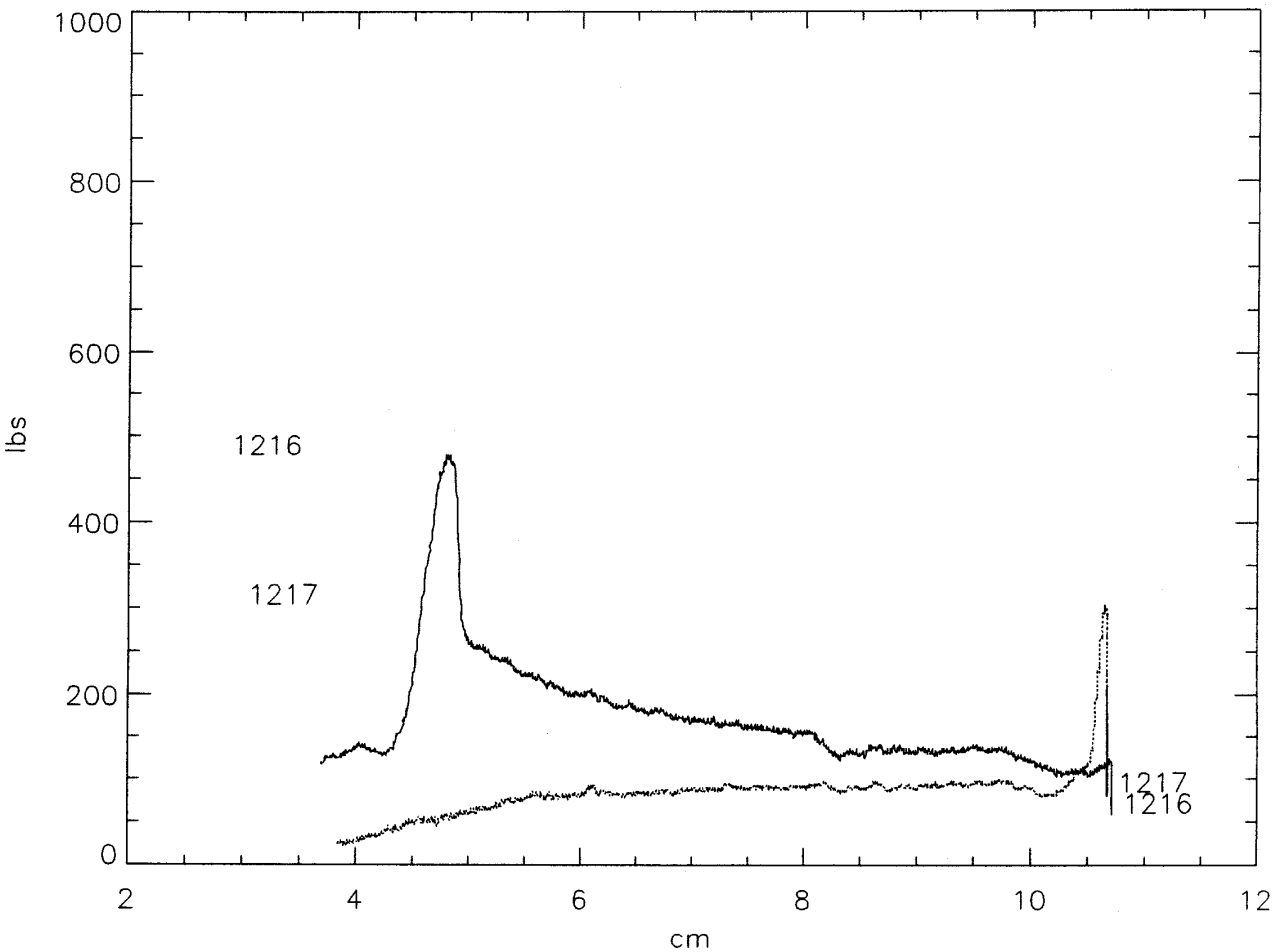




Shot	Material	Ram Speed, cm/s	TE2, K
1093	D_2	0.15	12.7
1117	D-T	0.15	13.2
1122	T_2	0.14	13.0

Shot	Material	Ram Sp
1088	D_2	0.
1155	T_2	0.

Typical extrusion force as a function of ram position curves for T_2, D-T, and D_2 which
conditions. As can be seen there is a definite progression $F_{T2}>F_{D-T}>F_{D2}$ at a given posi
as measured by the data acquisition system; the piston is going down from left to right
nozzle is located at ~10 cm. At the left-hand end of the curve (which is the most impo
where the highest forces are encountered) forces required for D-T extrusion are about 1
required for T_2 is 2 - 2.5 times that of D_2. These runs were recorded in conjunction wit
the dips in the curves occur where pellets are punched and fired. The extruder motion
interrupted at these points to help prevent jamming of the punch.



A comparison of two consecutive tritium extrusion runs in which very little additional tritium was added to the extruder for the second run. These typical runs show that a much higher force is initially required to start the extrusion than is required to maintain the extrusion at a constant rate. For the purposes of characterizing these data, the two regions will be separated and characterized by a static shear strength, responsible for the high initial force, and a dynamic shear strength, responsible for the behavior of the balance of the extrusion process.

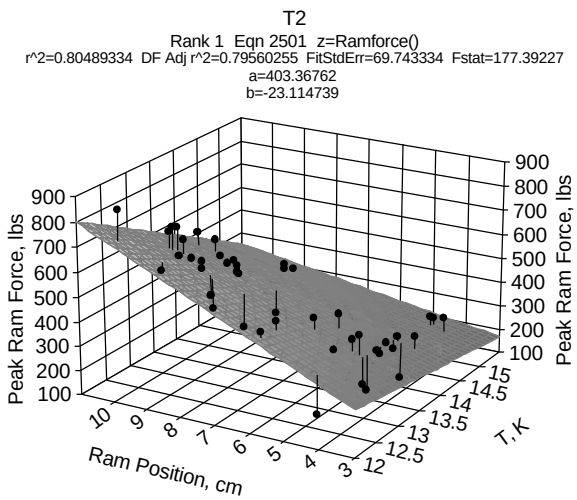
Die forces in these experiments were negligible because there is very little area re
nozzle. The peak force at the beginning of the extrusion $f(T, l)$ is a function of th
and length (l) of the billet contained in the extruder:

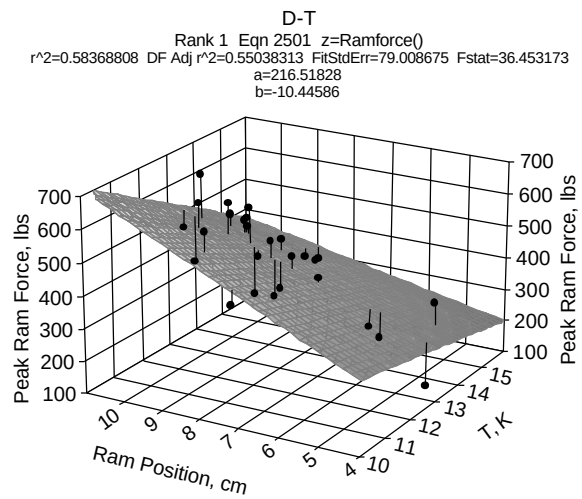
$$f(T, l) = f(Ram) + l P\sigma(T) \qquad (2)$$

where f(Ram) is the force required to overcome ram friction, P is the perimeter of
$\sigma(T)$ is the static shear strength of the ice. For the short temperature range involv
experiments it will be assumed that $\sigma(T)$ follows the linear function:

$$\sigma(T) = a + bT \qquad (3)$$

For this extruder P = 3.27 cm and l = 14.5-z (in cm) where z is the ram position
data acquisition system. Examination of runs in which there was little material ex
in Fig. 5) indicates that the ram force always levels off at about 100 lb_f prior to er
material, therefore, it is assumed that f(Ram) = 100 lb_f. TableCurve® 3D[14] was us
values of a and b from experimental data for the materials studied here; data fits a
and the parameters are summarized in Table 1.





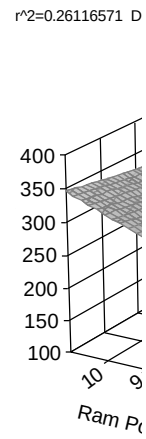


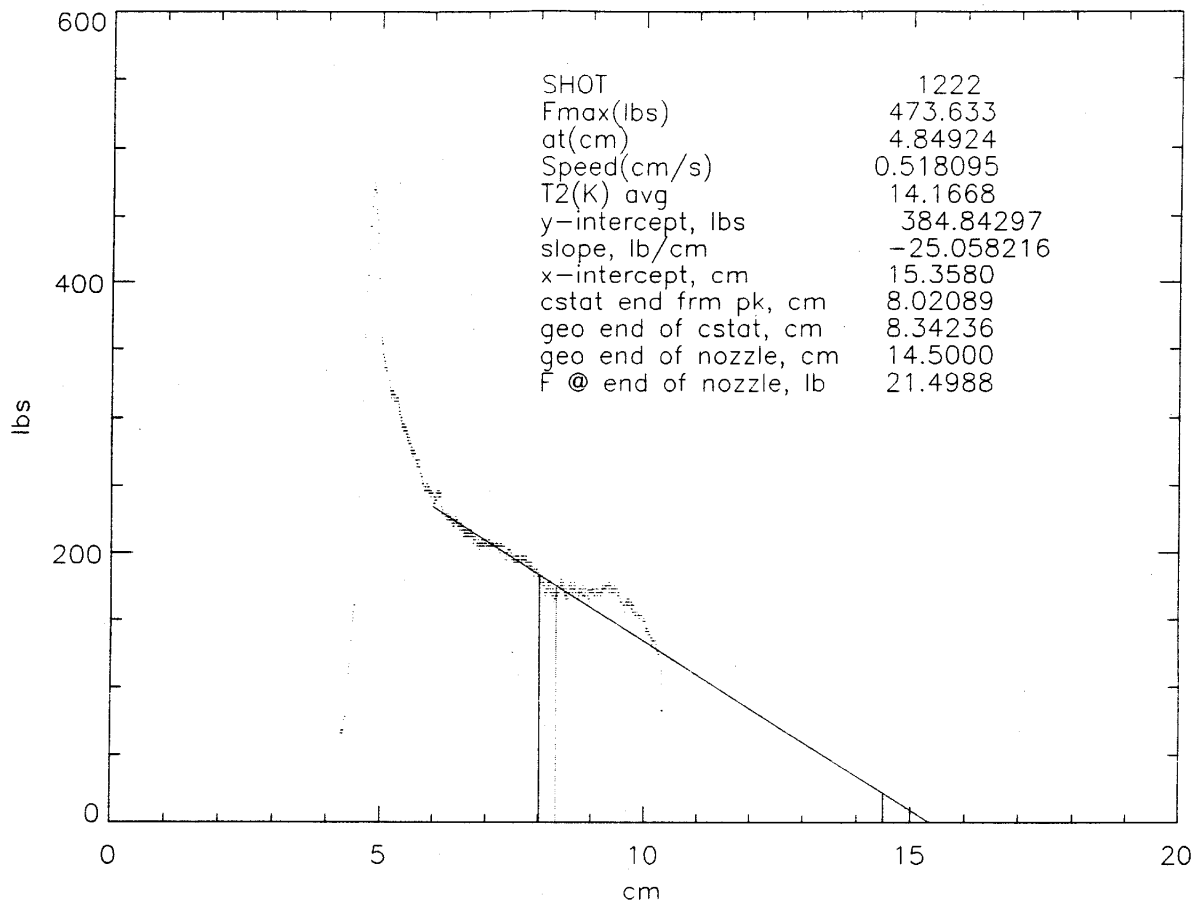
Table 1. Static shear strength parameters, s = a + bT.

Isotope	Temperature Range, K	a, psi	b, psi/K	a, MPa	b, psi
D_2	13 – 15	89.7	-3.6	0.62	-0.0
D-T	12 – 15	216	-10.4	1.49	-0.0
T_2	12 – 15	403	-23.1	2.78	-0.1

Determination of the dynamic shear strength σ_D of the material can be made from tl
using an equation similar to Eq. 2:

$$f(l) = f(\text{Ram}) + l P\sigma_D \qquad (4)$$

This equation indicates that the extrusion force should become a linear function of
initial static shear has been overcome. There are several problems that have been e
experiments that severely limit the usefulness of the data for determining this quant
apparatus was designed mainly for shooting pellets, the lower cryostat was not desi
enough to except the entire length of the extrusion, therefore, the extrusion hits the
cryostat before the ram is fully inserted. When this occurs, an additional buckling f
measurement that makes Eq. 4 invalid. This is illustrated below, which shows the l
squares method for the linear portion of the curve. The extrusion should hit the bot
when the ram reaches 8.3 cm and the end of the nozzle is located at 14.5 cm on this
between the end of the nozzle and the bottom of the cryostat). It is clear that the da
this point. Another interpretational problem is that the flow must be well developed
transition between static and dynamic behavior. This will occur only when the extr
at the start of the run, and even then there is only a narrow range between becoming
before hitting the bottom of the cryostat. To be consistent with the model the linear
best fit line to the end of the nozzle should have a force of zero or greater; and one
should be equal to f(Ram). The data shown below is assumed to be acceptable for t
it shows an extrapolated 21.5 lb.-force at the end of the nozzle. Data which does no
to the nozzle was not used in this analysis.

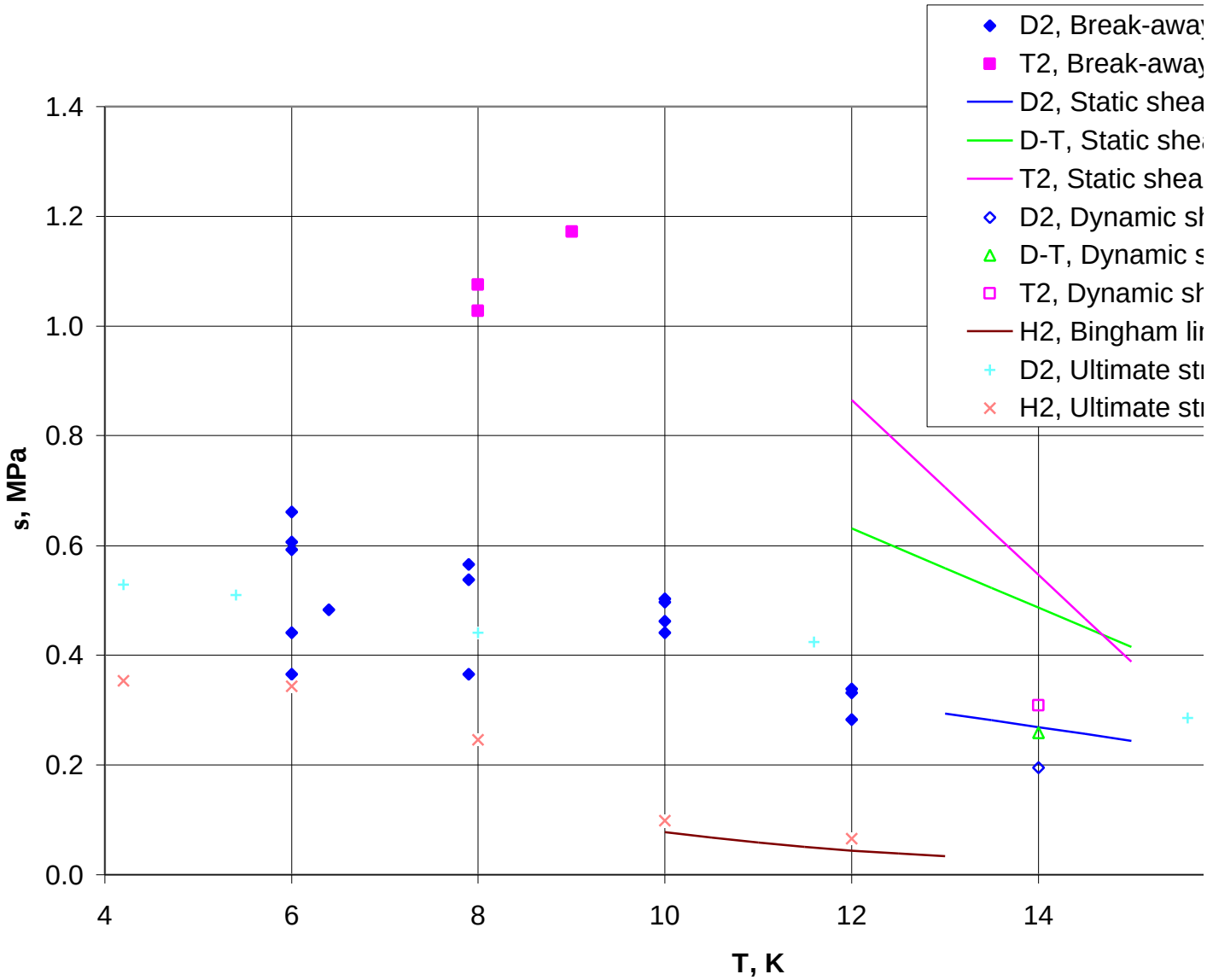


Shot 1222 data with fit to linear portion of curve extrapolates to the

Excursion of data above linear fit at right is due to the extrusion hitting the bott

Table 2. Dynamic shear strength.

Isotope	Temperature, K	s_D, MPa	s_D / s
D_2	14	0.194	0.72
D-T	14	0.259	0.56
T_2	14	0.308	0.53



Static shear strengths are also plotted as a function of temperature above along with pressures measured in the TPOP[6,15] experiment. Agreement with the previously me literature data[16,17,18] is good. Dynamic shear strengths at 14 K are also plotted here.

CONCLUSIONS

The TPOP-II experiment has shown that both T_2 and D-T pellets si
fusion reactor fueling, can be fabricated and accelerated using meth
been developed and tested with D_2. Operating temperatures for fab
like extruders appear to be similar for all isotopes. Extrusion press
however, larger for the heavier isotopes. It has been shown that rel
levels are acceptable in an extrusion based system, however, a large
consecutive fills have not been made to simulate accumulation in th
fully establish the maximum acceptable level. The decay heat in tri
prevent pellet formation and the pellets, once formed, do not rapidl
these experiments have been relatively limited and the physical pro
D-T have not yet been fully characterized, no adverse effects have b
which would bar their use in a centrifugal or pneumatic pellet fueli

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