Computational and Experimental Examination of Simulated Core Damage and Relocation Dynamics of a BWR Fuel Assembly – 16013

Gary Hanus *, Ikken Sato **, Tatsuya Iwama ***
* Phoenix Solutions Co
** Japan Atomic Energy Agency
*** Sojitz Machinery Corporation

ABSTRACT

The Japan Atomic Energy Agency (JAEA) plans a large-scale test to evaluate damage and relocation behavior of Boiling Water Reactor (BWR) core materials consisting of fuel rods (zirconia as fuel simulant), channel boxes, control blade assemblies as well as lower core-support structures. Its purpose is to contribute to the understanding of the core material relocation behavior in the event of severe accidents with the BWR design conditions for which existing experimental database is quite limited. Prior to large-scale testing anticipated at JAEA in the future, JAEA desires preliminary investigations to examine melting test pieces, being composed of a mixture of zirconia and metals by a non-transferred thermal plasma heating system. The purpose of such tests is to verify the materials and test piece will be heated by plasma as a primary heat source to the target temperature of ca. 2900K and to collect data about the relocation behavior of the high-temperature materials. This paper describes the first in a series of tests demonstrating the effective use of thermal plasma technology to recreate the dynamics of a typical fuel core bundle channel assembly section. Results from preliminary computational simulations of simplified fuel bundle assemblies are presented illustrating the effectiveness of a 150 kW, non transferred (NTR) configuration of a thermal plasma argon jet to heat the assembly within a highly-insulated containment vessel. An experimental test program using the computational analyses as a basis and a Phoenix Solutions Co (PSC) commercial model PT150, 150 kW plasma torch is described and the test results are presented illustrating the time versus temperature history of the fuel bundle assembly melting dynamics. Details on plasma operation are discussed including: power requirements, current flow, voltage levels achieved, argon gas flow rates, processing times and standoff distances of the torch discharge from the top of the fuel bundle assembly (achieved with remote control of the axial (vertical) translation of the torch within the containment processing chamber). Photos taken from the top of the processing chamber are presented illustrating the various phases of melting characteristics of the zircaloy-clad, zirconium oxide filled fuel tubes, all within a stainless steel tube bundle channel centered within an insulated zirconia crucible. Based on lessons learned from this initial test campaign, a brief discussion of the requirements and features of a follow-on Phase II test program is provided.

INTRODUCTION

JAEA plans a large-scale test to evaluate core degradation and core-material-relocation (CMR) behavior of fuel assemblies and control rods as well as lower plenum structures, using representative assembly materials including fuel (ZrO_2), zircaloy and stainless steels. Its purpose is to contribute to the understanding of core-degradation and CMR behavior, particularly under the design conditions of a Boiling Water Reactor (BWR). To evaluate such behavior JAEA plans tests to investigate fuel degradation and relocation behaviors in the event of severe accidents. Prior to large-scale testing anticipated in the future, JAEA desires preliminary investigations to examine melting test pieces, being composed of a mixture of fuel-like oxides and metals (zircaloy and stainless) by a non-transferred plasma torch system. The purpose of such tests is to verify the materials and test piece will be heated to the required high temperature level by plasma as a primary heat source to collect data about the relocation behavior of heated products.

As background, Figure 1 illustrates a meltdown dynamic scenario of a typical four channel arrangement of fuel rod bundles with control wiper between quadrant using a plasma heating system. Such an arrangement might represent a goal for test simulation during operation at a large-scale facility in JAEA in the future. However, in the near term, it is important to gain an understanding of the ability of thermal plasma to interact properly with representative fuel assembly components.

The following sections of this paper summarize an initial demonstration test for simulating the heat-up/melting dynamics of core subassembly components by concentrating on a ***simplified*** assembly as shown in Figure 2. With this arrangement, a subscale tube bundle melting test, consisting of a 5 x 5 tube arrangement within a bundle channel, was conducted, using representative materials of zirconia pellets in place of uranium oxide fuel and zircaloy-702 in place of zircaloy-2 fuel rod cladding.

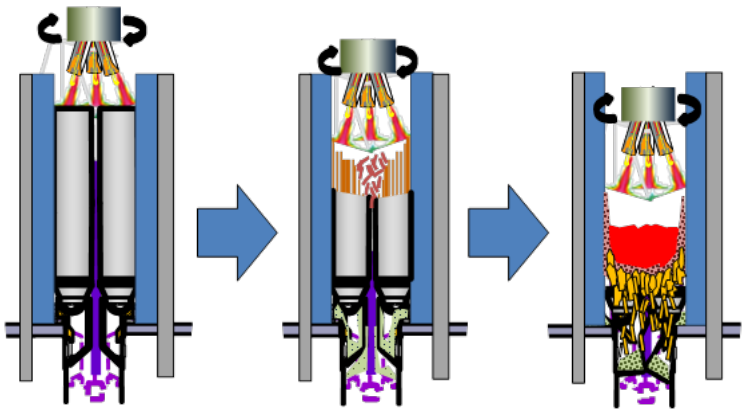

Fig. 1 Plasma Melting of Four Channel Tube Bundle Arrangement

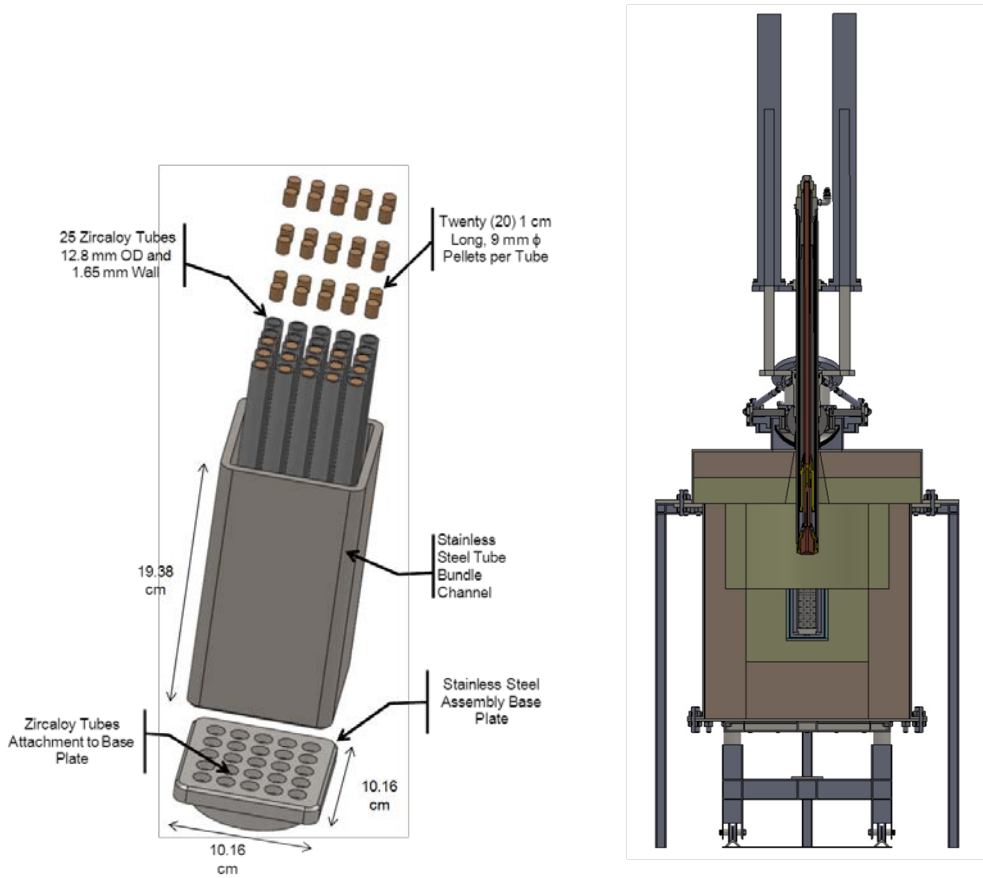

Fig. 2 Simplified Tube Bundle Assembly Showing Test Piece Assembled in Plasma Melting Chamber

METHOD

The equipment used for this melting test consisted of: (1) the test reactor, (2) the plasma heating system and (3) the test piece. The following sections provide details of the equipment.

Test Reactor

The test reactor used to perform the plasma melting test is shown in Figure 3. The test reactor features consisted of:

- Outer steel shell comprising the pressure boundary of the reactor vessel
- Within the shell are various layers of insulating material consisting of various combinations of refractory materials such as castable alumina, ceramic zirconia, fibrous zirconia and zirconia felt
- The “test article” is wrapped in fibrous zirconia felt material

- The reactor is designed with a removable cover/head, for ease of access

to the “test piece”

- The reactor cover is made up of several discharge/off-gas ports for the plasma gas, an optical access port for video recording of the melting dynamics, and a torch housing penetration that is equipped with a spherical ball gimbal and seal
- The torch and gimbal/seal are configured for appropriate manipulation for this test, allowing independent movement of the torch along it axis (i.e. axial drive in or out) as well as pitch and yaw, for full 3D coverage/manipulation, if needed of the plasma jet at or near the “test piece” melt zone.

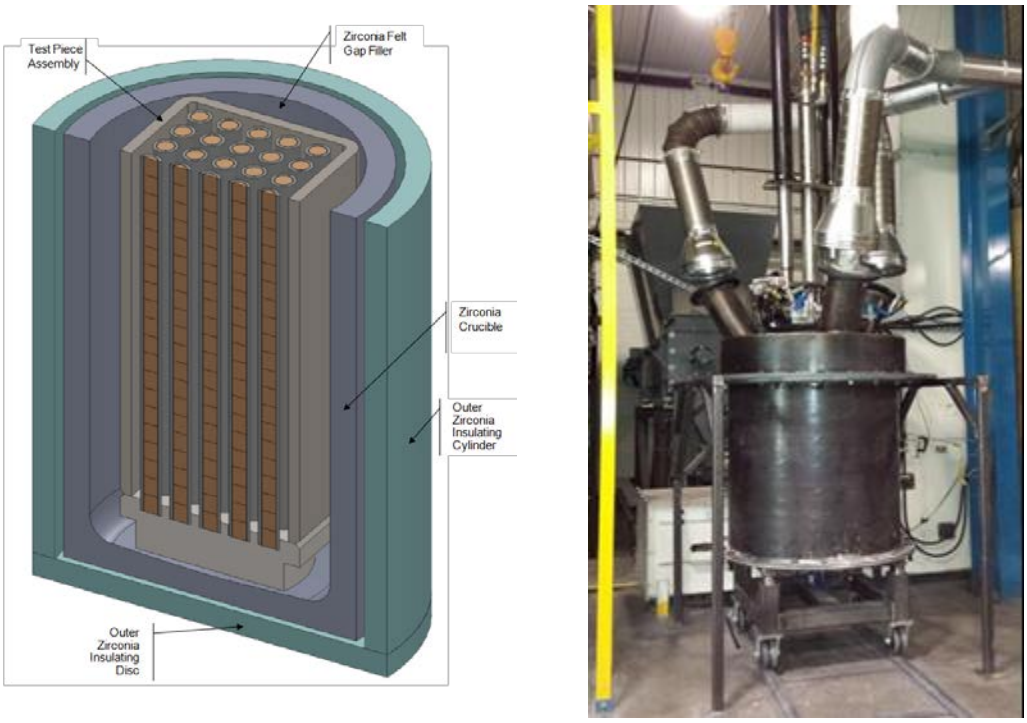

Fig. 3 Melting Chamber Test Piece Internal Insulating Configuration and Photo of Outside Details

Plasma Heating System

The plasma heating system used in this test program was a Phoenix Solutions Co, commercial-grade, model PT150 non-transferred (NTR) torch as shown operating below in Figure 4. The supporting subsystems to the torch included:

- Plasma power supply providing up to 150 kW to the torch
- Arc starter system
- Argon supply system with pressure and mass flow regulation/control
- Closed loop water cooling heat exchange system for the torch
- High pressure water cooling pumping system
- Hot side cooling water to air heat exchanger
- Complete control system for the plasma operation
- Instrumentation for monitoring plasma system operation
- Data acquisition and recording system for plasma and test operations

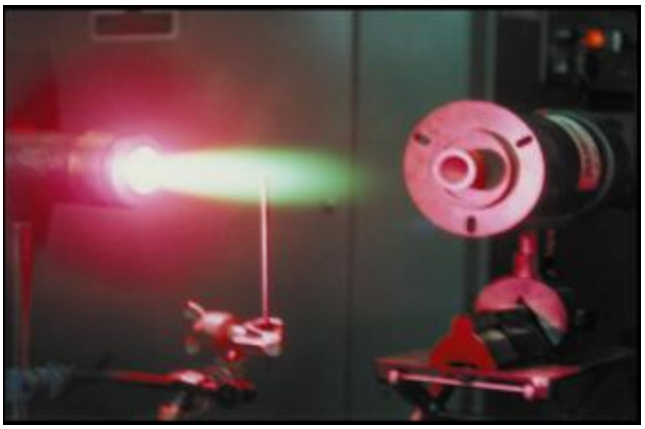

Fig. 4 Phoenix Solutions Co PT 150 Non Transferred Plasma Torch in Operation

Test Piece Description

The target assembly for the testing was a small test piece simulating a fuel rod bundle within a channel of a BWR. Zircaloy-clad tubes (5pcs x 5pcs) with length of 20 cm contained 500 pieces of ZrO_2 (melting point approx. at 2,700 deg.C) pellets with a length of 1 cm each. The zircaloy-clad tubes were housed in a metal canister or channel. The top of the clad tubes assembly was open and the tubes were fixed to a plate at the bottom end (closed end). Zirconia fiber insulation surrounded the test piece.

Figure 5 shows the overall details of an actual test piece assembly (outside test chamber and integrated within the insulated test vessel), illustrating:

- Top view illustrating the 5 x 5 tube bundle configuration, indicating the tube bundle encasement within a stainless steel, square channel of 10 cm x 10 cm
- Individual tube details illustrating use of 12.8 mm OD zircaloy tubes with a wall thickness of 1.65 mm for an tube ID of 9.5 mm
- Stacking of 20, 1 cm long zirconia pellets of nominal 9 mm OD within each of the zircaloy tubes
- Closed end (bottom) assembly base plate into which the 25 fuel rods are attached
- Open end (top) of the fuel rod assembly into which the plasma jet will flow and interact with the structure

Fig. 5 View of Assembled and Installed Test Piece

Computational Analyses of Test Pieces

A comprehensive, high resolution computational thermal/fluid dynamic (CFD) model was contructed of the basic test piece configuration to assist in understanding the thermal aspects of the tests, including preheating, melting and furnace internal refractory/insulation response. Figure 6 depicts the 1.2 million cell model of the furnace, which included the plasma torch input, upper gas plenum, test piece and surrounding furnace configuration. Fully three-dimensional, transient analsyes were completed to assist in understanding the best furnace design and materials selection to assist in effective test piece heating, up to and including melting. Figure 6 illustrates some typical results at 371 seconds into the start of a test, showing the details of the plasma plume temperatue and velocity distribution and the associated response of the test piece, including the zircaloy tubes, the zirconia simulated fuel pellets and the inter-tube, closed-end argon gas volumes.

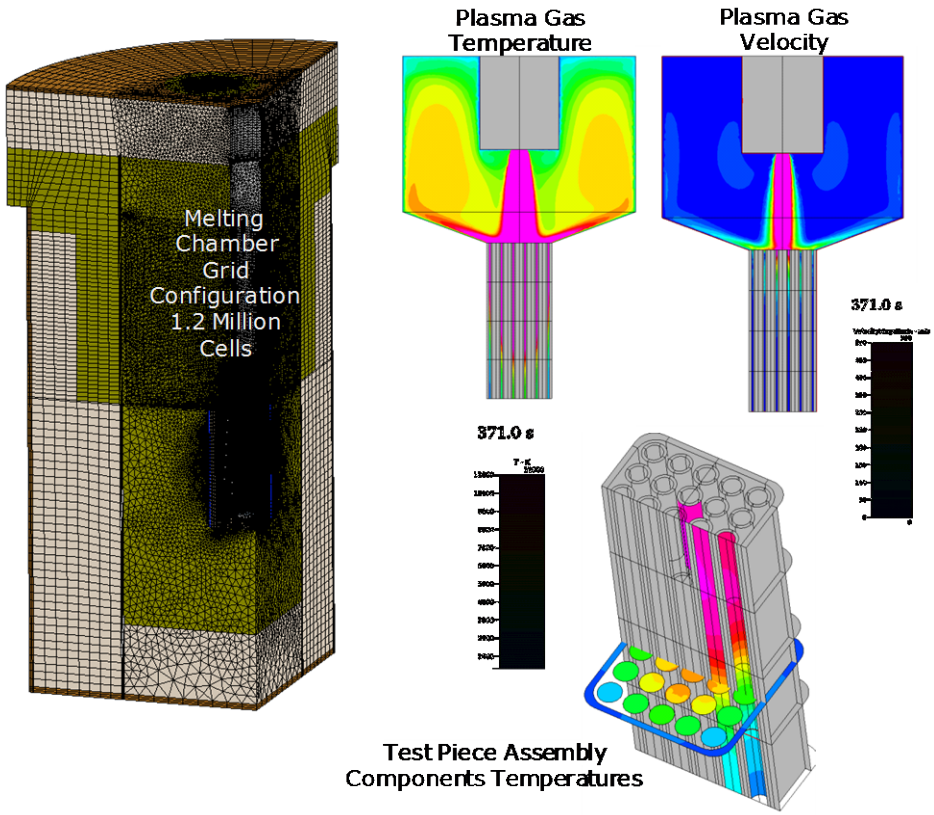

Fig. 6 Transient, 3D CFD Model and Results for Melting Furnace, Plasma Torch and Test Piece Assembly

Details of the 3-dimensional test piece thermal response is shown in Figure 7 below. Three tube locations are shown (center, inner and corner of the 5 x 5 matrix) with a plot of the corresponding axial temperature distribution (from base of the test piece to the top) at the center of the zirconia simulated fuel pellets. Four transient time frames are illustrated, from 30 to 180 seconds after the start of plasma heating. The plasma torch nozzle exit was positioned at 240 mm above the top of the test piece and the torch power simulated was 50 kW.

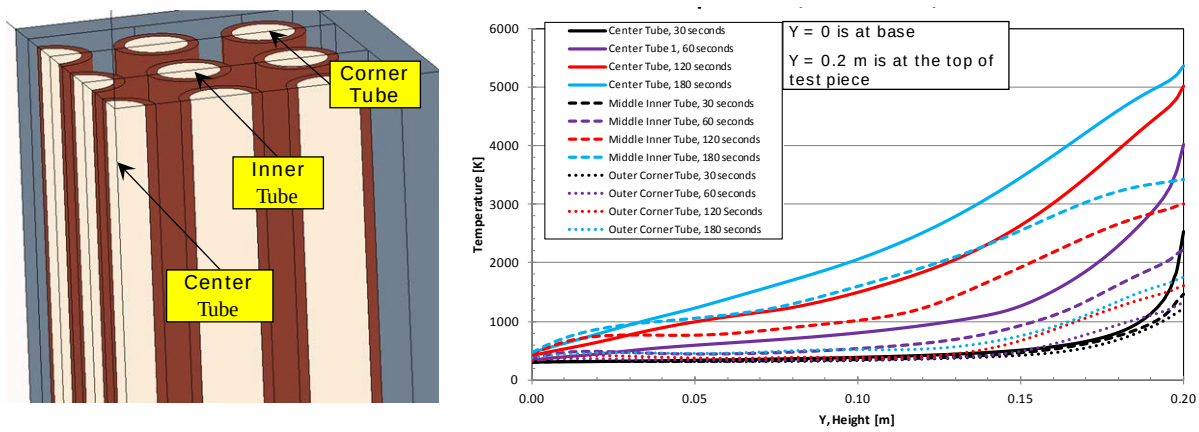

Fig. 7 Transient, 3D CFD Model and Results for Melting Furnace, Plasma Torch and Test Piece Assembly

The 3-dimensionality of the heating process is clearly illustrated for the axial direction. At the top of the test piece, height of 200 mm above the base, the variation in pellet heating is most pronounced, due to the largest temperature gradients that exist in the plasma plume as it expends from the torch nozzle exit and impinges on the top of the test piece. The centerline of the top of the center tube quickly reaches over 2500 K (in 30 seconds), while the most distant tube from the test piece centerline reaches only 1200 K. At 3 minutes into heating, these locations reach temperatures of over 5000 K and 1700 K, respectively.

Such CFD analyses as illustrated in Figures 6 and 7 provided the necessary guidance from which to position thermocouples and estimate timeframes in which test durations could be planned. As the temperatures climbed to quite high levels in short time frames just at predicted, the lifetimes of various thermocouples were known to be limited; however, valuable information was collected from these measurements, from test to test, to assist in setting subsequent operational test parameters levels to achieve certain exposure objectives.

TEST RESULTS AND DISCUSSION

Test Operational Details

Three tests were conducted to illustrate the test pieces' response to varying thermal plasma input power, gas flow and position of the torch above the test piece. Prior to each test a checkout was conducted of the plasma gas compression system, water cooling system , AC-to-DC power supply, torch manipulator, instrumentation/control system, data acquisition system, video monitoring and off-gas collection. During the testing of the three test pieces, torch height above the test piece, current, voltage, power and plasma gas flow rate were varied (as shown in Table 1 below) to affect the heating rate to the test article. Testing time from torch "on" to torch "off" conditions ranged from 23 to 160 minutes.

TABLE I. Range of Operating Conditions for Three Test Pieces

Test No.	Torch height above test piece, mm	Current, ADC	Voltage, VDC	Power, kW	Gas Flow, slpm
1	110-240	300-600	100-127	30-76	150-250
2	80-240	250-700	100-135	25-95	150-420
3	80-240	250-600	95-125	24-75	150-420

Results / Discussion

Typical results of the test campaign are summarized in this section with a focus on Test No. 1 only. Details of Test No.'s 2 and 3 are currently being evaluated and the results will be reported at a later date.

Test No. 1 was the longest duration test in which the torch was operated at a largest distance away from the target test piece and at a lower power. The purpose of this test was to provide preliminary operational response of the test piece to the integrated plasma and reactor combination. The duration of the test was approximately 85 minutes. Figure 8 provides a time sequence of the level of the operating parameters set during the course of the test. As can be seen, combinations of current and gas flow (voltage and power resulting), torch position above the test piece and holding time were recorded. Movement from one set point to another was decided by visual observations of the test piece as well as local thermocouple measurement within the test piece.

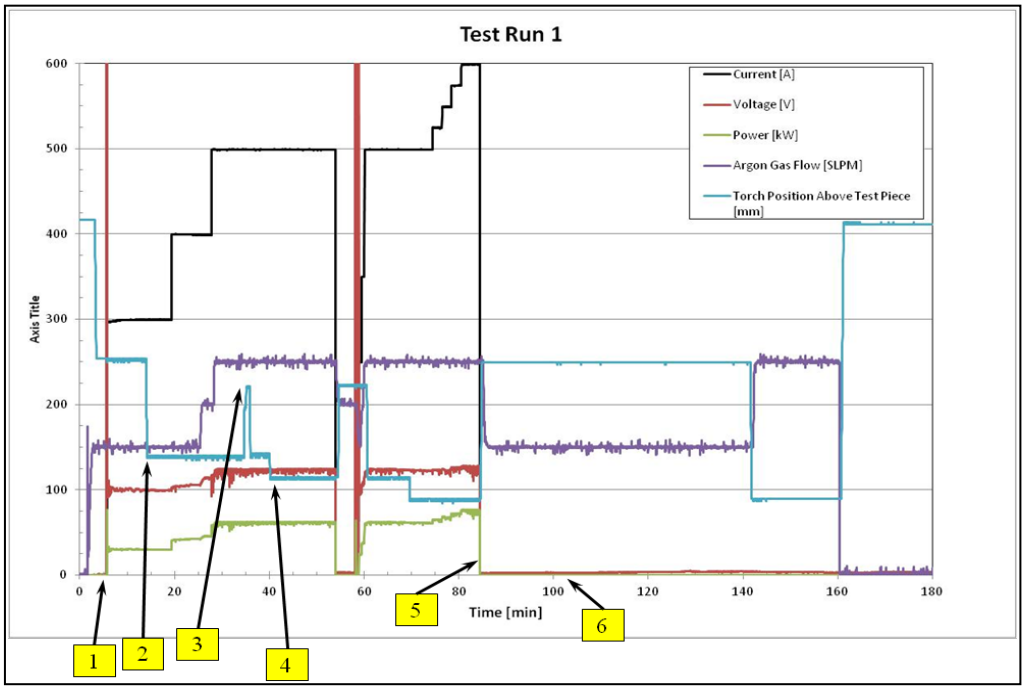

Fig. 8 Plasma Operating Conditions Used During the Duration of Test No. 1

Embedded within Figure 8 are several time-stamp markers (yellow numbered boxes) that are associated with changes in operating conditions that were expected to impart different heating characteristics to the test piece. A description of these marked events is as follows:

1) Torch "on"; position of torch at largest distance from the test piece (240 mm); power nominally at 30 kW
2) Torch moved closer to test piece (120 mm)
3) Torch moved farther away, temporarily for viewing, while power was increased to 60 kW
4) Torch moved closest to test piece (110 mm)
5) Torch heating "off" and moved away from the test piece (240 mm)
6) Test piece cooling prior to opening the chamber for test piece inspection; torch gas remained on (non-plasma cold argon)

Figure 9 shows photos of the test piece as viewed from the upper chamber of the reactor, indicating the visual condition of the test piece at time stamp No.'s 2, 4, 5 and 6. In the photo for time stamp No. 2 the test piece, zircaloy tube/zirconia pellet matrix is clearly seen with the plasma torch at its maximum distance away from the test article. Time stamp No. 4 photo shows the test article being heated at the maximum power and closest position. Time stamps No.5 and No. 6 show the conditions of the upper portion of the test piece immediately after the torch is turned off and during post test cool down, respectively.

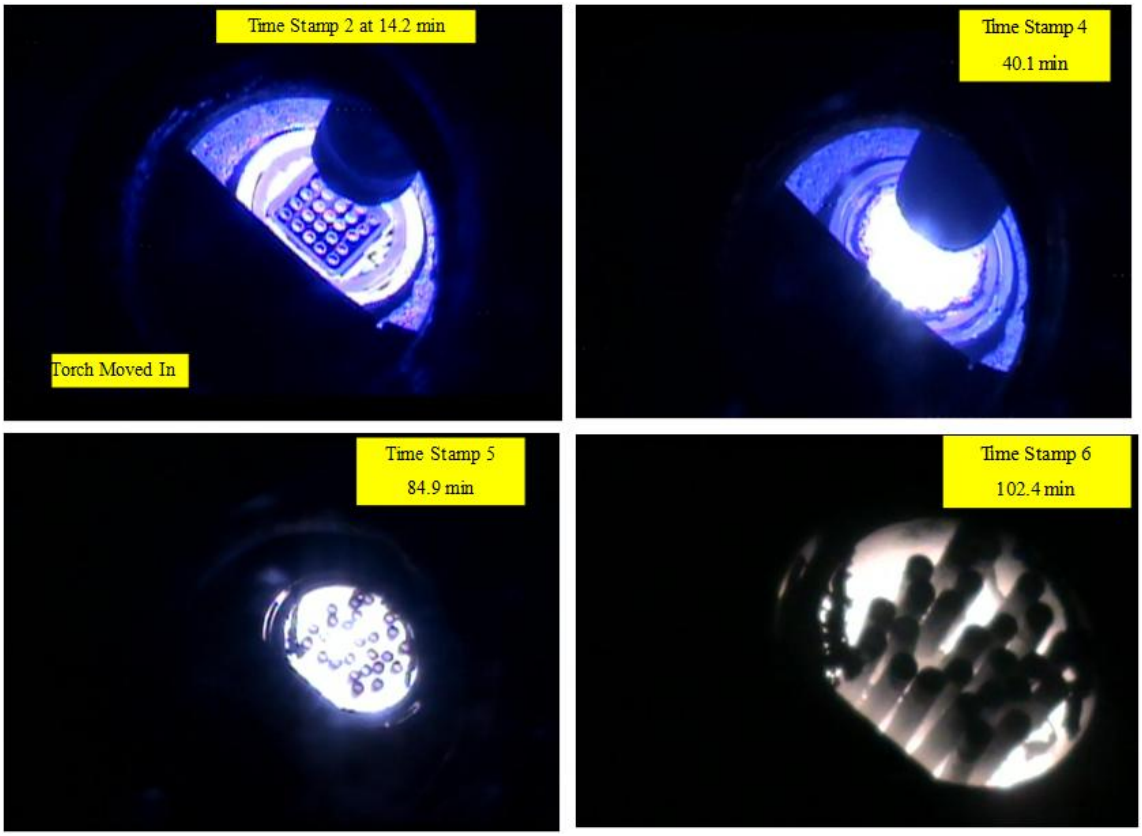

Fig. 9 Photos of the Test Piece During Plasma Melting Sequence

Because of the preliminary aspects of Test No.1 only partial melting and tube bundle collapse was observed. However the following observations were noteworthy in regard to decisions for follow-on testing in the campaign:

- The entire stainless steel tube surrounding the bundle melted quite soon relative to the zircaloy tubes and zirconia pellets, forming a large solid heat sink at the bottom by combining with the tube support base. This also contributed to an inordinate amount of thermal radiation loss.
- A large portion of the zircaloy tube assembly remained un-melted; however, there was evidence of mid-tube breakout releasing some pellets and molten inner part of the tube downward.
- A good deal of oxidation appeared to be ongoing during the test, as evidenced by the thinning walls of the zircaloy tubes that remained standing. This oxidation was probably due to a small amount of ambient air being circulated inward via the exhaust ports as a result of the hot gas ducting, educator feature used for removal of the plasma gas. The oxidation feature was noted to be significant, though not intended, as it replicates the fact that oxidation does occur in the actual core meltdown scenario.

Figure 10 illustrates the final condition of test piece No.1 after cool down and during inspection. Tube collapse, some mid-tube breakout of pellets, and indications of oxidation can be clearly seen.

Fig. 10 Photo of Post Test Condition of Test Piece No. 1

CONCLUSIONS

It has been demonstrated that the use of thermal plasma is an effective test tool to impart sufficient, directed thermal energy to a simulated fuel bundle channel to affect melting dynamics in a way representative of what may occur in an actual core meltdown scenario. To be reported at a later date, the use of the plasma in the Test No.'s 2 and 3 clearly was able to achieve a simultaneous melting and movement of the zircaloy-clad, simulated (zirconia) fuel pellets. This melting dynamic demonstration provided the impetus for additional testing of larger-scale, more complex core configurations. This larger-scale, follow-on test program is now in progress.