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HIGH CURRENT DENSITY, CRYOGENICALLY COOLED
SLIDING ELECTRICAL JOINT DEVELOPMENT

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ABSTRACT

In the past two years, conceptual designs for fusion energy research devices have focussed on compact, high magnetic field configurations. The concept of sliding electrical joints in the large magnets allows a number of technical advantages including enhanced mechanical integrity, remote maintainability, and reduced project cost. The rationale for sliding electrical joints is presented.

The conceptual configuration for this generation of experimental devices is highlighted by an ~ 20 T toroidal field magnet with a flat top conductor current of ~ 300 kA and a sliding electrical joint with a gross current density of ~ 0.6 kA/cm². A numerical model was used to map the conductor current distribution as a function of time and position in the conductor. A series of electrical joint arrangements were produced against the system code envelope constraints for a specific version of the Ignition Studies Project (ISP) which is designated as 1025.

Sliding electrical joint performance is detailed with regard to peak current density, thermal response (for a one second pulse), average current density (16 s), i^2t , design operating life, and margin to failure.

A number of sliding joint concepts have been investigated although only the most successful configuration is reported.

The demonstrated performance, presented in terms of measured levels, and required design levels are summarized:

- Hundreds of 10 s shots >4 kA/cm²; design: 0.6 kA/cm²
- More than 2×10^5 mechanical cycles; design: 10^5 cycles
- More than 3×10^4 full power pulses; design: 10^4
- 1050°K thermal excursion without failure; design current level: 250°K

- Hundreds of pulses with i^2t equal to $180 \times 10^6 \text{ A}^2 \cdot \text{s/cm}^2$; peak design level: $6 \times 10^6 \text{ A}^2 \cdot \text{s/cm}^2$

A final discussion is presented which details a viable sliding electrical joint configuration, highlights outstanding technical issues, and scopes future work.

INTRODUCTION

The Princeton Plasma Physics Laboratory (PPPL), part of Princeton University, has recently been studying concepts for compact, liquid nitrogen (LN_2) chilled, high magnetic field tokamaks. The tokamak, a specific experimental device configuration in the field of controlled thermonuclear fusion, relies on the confinement and heating of a toroidally shaped plasma. The major magnetic confining field for a tokamak is the Toroidal Field (TF). Inherent in the tokamak configuration is an induced current which provides enhanced confinement and resistive heating which results in the initial stages of the plasma temperature excursion. The probability of achieving a controlled thermonuclear burn is dictated in part by the magnitude of the Toroidal Field.

The Toroidal Field Coil (TFC) is a focal point of technical concern and cost. The TFC dictates the size, location, and configuration of a number of other tokamak systems.

The first portion of this paper summarizes the rationale for considering a sliding electrical joint in the TFC. The operational requirements for the sliding joint are presented, based on a numerical model of the conductor current distribution and a tokamak configuration designated at PPPL as 1025. A sliding joint concept is then detailed and PPPL's High Current Test Laboratory capability is specified.

The test results presented are limited to a single contact concept and performance topics include:

- contact pulse resistance
- thermal response
- equilibrium performance
- failure mode

- mechanical wear of the contact surfaces
- optimum contact pressure
- coefficient of friction
- lubrication requirements
- power dissipation capability
- temperature sensitive properties
- current sensitive properties

A discussion is presented on induced failure of the sliding contact. The demonstrated performance of this contact concept and the required performance are compared as operating margin. Future work is scoped and includes efforts to optimize performance, establish a statistical basis for predicting reliability, and an effort to extend operating margin.

RATIONALE FOR CONSIDERING A SLIDING ELECTRICAL JOINT

The traditional focal point in the design of a tokamak has been the TFC. As indicated on Figure 1, each TFC is arranged such that its radial inner leg is simultaneously wedged and aligned against a central cylinder. In this arrangement, both adjacent turns and the central cylinder restrain the TF inner leg which is subjected to a magnetically driven centering force. This same inner leg is exposed to a significant Vertical Separating Force (VSF) which in this configuration exceeds 700 MN for the entire TF system. Critical economic and engineering trade-offs are performed, focussing on the cross section of the TF inner leg and its effects on other systems.

Overall tokamak size, cost, and TF stored energy are directly dependent on the radial build of the TF inner leg. Further, the TFC inner leg is inaccessible for repair even before the tokamak becomes radioactive and remote maintenance becomes a necessity. A sliding electrical joint, therefore, offers numerous benefits:

1. With the redistribution of the VSF the TF inner leg stress may be reduced, the coil cross section may be reduced, or lower strength, higher conductivity conductor materials may be used.
2. With the incorporation of a sliding joint, the TF inner and outer leg are mechanically segregated, in-plane moments are reduced, and restraining structure beyond the coil cases may be derated.

3. The type of sliding joint to be detailed offers a three-dimensional relief in fabrication and assembly tolerance. Since the joint can accommodate slide in the coil plane, the in-plane tolerance for coil fabrication may be significantly relieved. This specific contact design also allows mechanical compliance in the direction perpendicular to the coil plane. It has been demonstrated that the contacts operate satisfactorily over a 2-1/2 mm range of compression.

4. The concept of a sliding joint allows straightforward assembly and credible remote maintenance, access, and disassembly.

5. As shown in Figure 2, the sliding joint concept affords access to the TF bore. A number of subsystems can be considered unitized, preassembled, and tested as a complete unit. For example:

- The vacuum vessel need not have parting joints and a sectorized geometry.
- The PF coils can be located within the TF bore (a more magnetically efficient location) without the traditional compromise of being permanently trapped.
- The vacuum vessel liner and tiles may now be considered permanently mounted on the vessel. When significant tile replacement is required, a new lined vessel may be installed.
- The OH solenoid may be installed radially beyond the inner TF leg, within the TF bore which allows a reduction in size and power due to the proximity to the plasma.

6. A cost benefit study has been performed which indicates each of the four subsystem configurations listed within item 5 above would offset the cost of the sliding joint.

7. The concept of a sliding joint is consistent with repair of a TF outer leg by simple replacement.

In summary, the concept of a sliding electrical joint in the TFC enhances the mechanical design margin for the coil and surrounding structure, allows realistic remote maintenance, and offers significant cost benefits.

PROBLEM STATEMENT

The tokamak configuration which served as the basis of the mechanical layout for this sliding joint consists of a two-layer TF coil with copper

plate conductors. The area allotted for the sliding joint is 12.7 cm by 18 cm high in a region where the conductor is 3.3 cm thick. In order to characterize a sliding joint the concept of gross current density (GCD) was adopted. The GCD is defined as the total current through the joint divided by the total area required for the joint assembly, including mechanical support and packing efficiencies.

The design TF current waveform consists of an 8 sec ramp up to 290 kA, a 4 sec flat top at 290 kA and a 4 sec ramp down (the system power supplies would invert and drive the current down).

A numerical model (Reference 1) was constructed to study the current and thermal distribution during the 16 sec current profile. The model was based on the conductor geometry of the inner TF leg, inner turn at the machine midplane. The numerical current distribution represents a worst case current density when applied to the joint area since the modelled conductor contained 15% less material than the conductor in the joint region. The model assumed OFHC (oxygen free, high conductivity copper), included the temperature dependence of electrical resistance and the thermal conductivity of the copper, but did not account for nuclear heating. Figure 3 illustrates the current density distribution map for a conductor which has been divided into ten zones. The current density contours are marked with the time during the 16 sec pulse. For instance the contour marked "8" is the current distribution at the eighth second, the end of the current ramp up. Note the dramatic swing between the 12th and 13th second when the power supplies invert.

The numerical plot was then compiled as a table of 1 second peak currents and i^2t levels for each of the ten zones and each of the sixteen time slices during a shot. The electrical contact is derived from a Westinghouse Electric Corporation component which has the part number 5614C76G01 and is detailed in Reference 2. The current and i^2t profiles are compiled against the specific geometry of this Westinghouse contact, the 1025 design base, and is illustrated in Figure 4.

The bottom portion of the figure details the peak current per contact in each zone for each of the sixteen time periods, the average contact current in the zone and the maximum, 1 sec contact current.

The upper tabulation in Figure 4 is a compilation of i^2t for each zone for each of the sixteen periods of time. Each zone in the pictured configuration contains sixty Westinghouse contacts (six columns of five contacts each on two sides of the conductor). For example, during the first second of the model, Zone 1 passes $14 \times 10^6 \text{ A}^2\cdot\text{s}$. Since there are sixty contacts in a zone, each contact would carry less than $0.25 \times 10^6 \text{ A}^2\cdot\text{s}$. The second to the last column in the same table compiles the integrated i^2t for each zone. The total i^2t through zone 1 is $284 \times 10^6 \text{ A}^2\cdot\text{s}$ or less than $4.75 \times 10^6 \text{ A}^2\cdot\text{s}$ per contact. The last column compiles the one-second maximum i^2t for each zone.

The upper half of Figure 4 illustrates the TF coil configuration, the sliding joint area, the zone partitioning, and a two-view, dimensioned layout of a zone with the Westinghouse contacts illustrated.

From the numerical analysis and the conceptual layout above, the following characteristics are compiled and represent a level of performance required to demonstrate feasibility.

Figures 5 and 6 illustrate the sliding joint concept and the 24-contact test fixture, respectively.

Although the feasibility of the candidate joint must be demonstrated to the i^2t and current capabilities summarized in Table 1, significant additional parameters must also be addressed, including:

- 1 cm excursion under power
- 10^4 full power cycles
- 10^5 half power cycles
- 1 mm/sec slide speed
- low joint resistance

FEASIBILITY DEMONSTRATION PLAN

The national fusion community program to demonstrate sliding joint feasibility involved parallel efforts at a number of laboratories leading to the identification of eleven sliding joint concepts, one of which incorporated the Westinghouse contact.

References 3 and 4 detail a number of activities including a literature search which resulted in a compilation of over 125 papers, a workshop held at

PPPL which focussed on high current electrical joints, and a number of generic sliding joint concepts.

Informal consensus was reached as a result of the PPPL-sponsored workshop which helped in formulating the sliding joint feasibility demonstration plan. A few of the more important program guidelines were:

- establish the failure regime of the concept
- the ultimate test assembly should approach a 5 - 10% scale of the actual joint -- no parameters other than joint area should be scaled.
- thoroughly characterize operating parameter interdependencies.

A number of performance factors were judged to be beyond the budgetary scope and time constraints of the program. These excluded activities were:

- statistical reliability,
- operation of the sliding contact in a background magnetic field oriented perpendicular to the TF current,
- iteration of the sliding joint design to extend operating margin.

The feasibility demonstration effort at PPPL started with the construction of a High Current Test Laboratory, which includes:

- a power system capable of delivering 25 kA and 5 V continually and 35 kA for a limited pulse length,
- a universal test stand which provides mounting for the contact, variable contact pressure, slide motion, and variable slide speed,
- a computer-based instrumentation and data processing system.

POWER SYSTEM

The High Current Test Laboratory Power System is fed from a 480 V, 3 ϕ , 500 A service, protected and controlled locally by a size 5 combination motor starter. The system voltage adjustment is achieved by three ganged 32 kVA powerstats. Three independent power supplies are paralleled for high current operation and each consists of a delta/star step down transformer (480/5) and a six pulse rectifier with each leg composed of two parallel 1200 A RMS SCRs. On/off control is achieved by gating the SCRs from a digital-timer-driven, 25 amp transistor. The SCRs and connecting buswork are water cooled. Cooling, personnel, thermal, and operating range interlocks are incorporated into the power system.

Figure 7 illustrates the three transformers and a portion of each water-cooled rectifier stack in the background. Note at the right the DC generator shunt (20 kA/50mV) and the flexible bus of copper foil.

TEST STAND

The test stand consists of a fixture to support the two halves of the sliding joint, a load table with a counterweight system, thermal and electrical breaks (to isolate the test contact), a motor-driven slide table (with a range of slide speeds and stroke length), a N_2 delivery system, and a strain gauge bridge to measure the coefficient of friction. The slide motion is coordinated with the SCR gates and the extent of the excursion is limited by the pulse duration and electromechanical limits. The test stand is compatible with liquid nitrogen operation and consumes, at maximum power and repetition rate, 50 liters of N_2 an hour. Figure 8 details the test stand.

INSTRUMENTATION AND DATA PROCESSING

An Analogic Data 6000, four-channel digital waveform analyzer with dual disk memory is the main data gathering and processing element.

There are four analog signals monitored for each shot:

- the contact voltage drop waveform
- the current waveform
- the body temperature waveform of a selected contact
- the strain gauge bridge

The Data 6000 archives the monitored waveforms, and stores an array of calculated values representative of each shot. Included in this numerical array is the RMS value of current, RMS voltage drop, the prepulse contact temperature, the magnitude of the contact body temperature excursion, the peak temperature, the calculated power, contact pulse resistance, i^2t , and the shot number. A Gould eight-channel pen recorder, which is pictured in Figure 7, is used to monitor additional temperature waveforms and process the raw thermocouple signals. The numerical array summary (parameter trends) of each waveform has proved to be essential when studying long term trends which develop over hundreds or thousands of shots.

The nature of the low level signals, the requirement for significant accuracy, 25 kA biased monitoring points, and substantial magnetic field interference dictated that the instrumentation be carefully designed and frequently checked for calibration. Each of the key waveforms were optically isolated to ensure electrical reference integrity.

TEST FIXTURES

Three test fixture configurations were established to evaluate the Westinghouse contact:

- A test fixture with three in-line contacts, each equipped with a thermocouple, where the outboard two contacts were insulated from the lower collector bus with a total of ten mils of Kapton.
- The same in-line fixture with six contacts in the assembly and each contact separated from its neighbor by a 1 mil spacer of Teflon, see Figure 9. This assembly has capacity for twelve contacts without the spacers.
- The twenty-four contact assembly illustrated in Figure 6 and Figure 10.

Single Contact Test

The assembly with the single active contact was intended to characterize a number of factors including:

- the influence of contact pressure on contact resistance,
- the effect of varying pulse length (1, 2, 3, 4, 6, 8, 10, 15 sec),
- the thermal response of a single contact as a function of varying initial temperature and current level,
- the performance of a contact with maximum heat sinking.

In addition, by arranging the passive contacts to ride on a surface which was ten mils higher than the active contact (because of the insulating Kapton tape), the recorded performance represents the case of significant surface irregularity.

The single active contact test represents the most optimistic thermal arrangement and eliminates any current sharing effects observed in configurations with multiple parallel current paths. Figure 11 illustrates a

portion of the data compiled with a single contact. Over one hundred shots are represented by the five least squares fit curves. The majority of data points are deleted for clarity. Several important trends are evident:

- for pulse lengths slightly longer than three seconds the single contact, traveling at 1 mm/s has reached thermal equilibrium independent of the contact current level,
- the one second current pulse capability is fifty percent greater than the fifteen second capability,
- extensive operation in the temperature range indicated (less than 700° K rise) demonstrates good repeatability and no long term degradation.

It should be noted that the temperatures of the adjacent contacts were continually monitored. The Kapton film insulating the outboard, passive contacts occasionally wore through, but this was immediately detected when the temperature of the "passive" contact rose and the temperature excursion of the active contact was suppressed.

The single active contact configuration was the arrangement used to establish the failure point for the contacts.

Six Contact Test

The fixture used in the single contact test could be modified to hold six, eight, or twelve contacts in a single line with the appropriate pressure provided by the load table. Both six and twelve contact arrays were run extensively. The data presented in Figure 12 are for the six contact arrangement. The purpose of the six contact operation was to:

- study current sharing between contacts,
- establish the coefficient of friction over the potential operating range and during wear-in, the first few hundred cycles for a new contact,
- study how the pulse contact resistance varies with temperature and current,
- accumulate several thousand shots of operation.

As indicated in Figure 12, the current balance between contacts does vary. The four temperature bars indicate the range of recorded temperatures

for the six contacts in the array at four specific current levels. The temperature bar was based on over four hundred shots where the strip chart records of each of the six contact temperatures were reviewed. Typically when one contact showed an exaggerated temperature rise because of an increase in contact current, the current excursions of the remaining five contacts were depressed. The vertical bars on Figure 12 illustrate the upper and lower range of temperature excursions at the current levels indicated. In general, no current sharing pattern was observed and individual contacts could not be identified as light or heavy current carriers, regions in the array did not tend toward a specific current density, and contacts immediately adjacent to a momentarily higher current carrying contact did not tend to be either warmer or colder.

In summary, no hot spots or cold regions could be identified and, in general, the current carrying variations were slight.

The wear-in behavior of the contacts, specifically the changing values of pulse resistance and coefficient of friction, proved to be a surprisingly short term phenomena. The coefficient of friction of a lubricated new set of contacts would decrease from 0.15 in a hundred cycles to an equilibrium level near 0.10. The coefficient of friction did not change with current level or pulse duration, could not be correlated with changes in electrical or thermal performance, and did not vary significantly after a thousand shots or when operation approached the thermal failure point.

The assembly pulse resistance settled to an equilibrium level within the same one hundred cycles as the coefficient of friction. However, the resistance wear-in could be accelerated if high power pulses were applied instead of shots in the range of 200-300 amps per contact. The pulse resistance would decrease by up to 20% for constant temperature, low power wear-in cycling. Eventually the standard procedure was to ignore the wear-in and proceed to high power shots even on new contacts.

Twenty-Four Contact Test

Figures 6 and 10 illustrate the twenty-four contact array. The slotted portion of the assembly was bolted to the lower test stand bus which experienced the slide motion during the power pulse.

The original design provided channels for the LN_2 , but this technique was abandoned due to the extensive cooldown time between shots. The alternate configuration (pictured in Figure 8) involved immersing the lower power bus in an LN_2 pool contained by a G10 dewar.

The goals of this series of tests were:

- examine an $\sim 5\%$ area joint,
- examine current sharing with 24 parallel paths,
- examine the performance of a joint where the contact pressure is fixed by the gap in the mating bus,
- examine the electrical and temperature performance when the contacts are packed together,
- examine the repeatability of performance for very high assembly currents,
- examine how the concept of a free floating, self-aligning contact assembly works over hundreds of cycles.

The twenty-four contact assembly was subjected to a series of shots which were restricted to 10 sec and 15 sec long pulses. The 10 sec pulse is the equivalent square wave of the prescribed TF ramp up, flat top and ramp down. The assembly and alignment of the twenty-four contact array proved to be far easier than any previous configuration. Two types of temperature rise vs current curves were observed in six runs which totalled 1904 shots. The first type of trace indicated that the temperature rise trend essentially leveled out at 200°K at currents greater than 500 A per contact. Each time this occurred the test fixture was found to be mechanically bound. The assembly was wedging to the side which contained the three instrumented contacts. Since the pressure on those contacts was higher, the voltage drop, the dissipated power, and therefore the contact thermal excursion were suppressed. The misalignment was a result of the method of securing the 25 kA bus, a condition which was exaggerated when the assembly was cooled down to LN_2 temperatures. A rearrangement allowed the contact assembly to float freely in the horizontal plane but to be restrained in the vertical plane. This restraint was necessary to resist the 25 kA-driven magnetic forces on the bus and assembly. Figure 13 illustrates the contact temperature rise vs current for the last two runs of the twenty-four contact assembly. The solid line is the least squares fit to the data indicated. Note that the profile

exhibits the double inflection which was also evident for both the single contact and the six contact arrays.

Figure 14 focuses on the temperature rise vs current profile of the last run for the twenty-four contact assembly. The curve fit is limited to the 130 points from run 6 and the curve double inflection is more apparent. The error bars overlaid on the curve were obtained by examining specific digitally stored data points within a 25 A range. The height of the error bar marks the extent of the temperature excursions recorded. The number on the bar indicates the number of data points examined within the indicated 25 A range of current.

Data Collection

Figure 15 is an example of a 225 shot data excerpt of a sequence which was intended to characterize single contact performance as a function of temperature, pulse duration, and current level. Each shot was extensively monitored and archived. The following characteristics were compiled and stored with the shot number label:

- current waveform,
- voltage drop waveform,
- contact body temperature waveform,
- value of the RMS current,
- value of the RMS contact voltage drop,
- pulse resistance of the contact,
- contact power dissipation,
- i^2t through the contact assembly,
- peak contact body temperature,
- prepulse contact body temperature,
- contact body temperature excursion.

With this detail of information, any specific shot may be reexamined at a later time, parameter trends may be constructed, or one parameter plotted against others. Figure 15 is an example of eight parameters compiled for approximately 225 shots. Shots 290 to 350 are records of a cooldown of a single contact assembly. The remainder of the record is dedicated to mapping the thermal characteristics (i^2t) of the contact where current level and pulse duration are systematically varied.

Thermal Time Constant Study

A single contact was monitored as pulse duration was increased for a fixed contact current of 2.7 kA. Figures 16 and 17 represent a portion of the data. The pulse widths represented are 1, 2, 4, 6, 10, and 14.5 seconds while the i^2t ranges from $7.3 \times 10^6 \text{ A}^2\cdot\text{s}$ to $105 \times 10^6 \text{ A}^2\cdot\text{s}$. From this series it was determined that thermal equilibrium is reached in essentially four seconds for the single contact array and in approximately three seconds for the array where contacts were tightly nested - such as the 24-contact assembly.

Figure 18 shows the current and temperature waveforms for a single contact exposed to a typical 3 kA, 15 sec square wave which has a thermal equivalent of $135 \times 10^6 \text{ A}^2\cdot\text{s}$.

Variable Current Study of Twenty-Four Contact Assembly

Figure 19 illustrates waveform progression of the assembly current, assembly voltage drop, and contact body temperature as the current for the twenty-four contact assembly was raised from 8.1 kA (0.34 kA/contact) to 25.4 kA (1.06 kA/contact). Note that the voltage waveform consistently has a high leading edge (0.15 to 0.25 v) which settles to a level which is a function of the current density. The contact voltage drop waveform has been found to be the best indicator of stable sliding joint operation. Large differences between the leading edge and the flat portion of the voltage waveform indicate less than optimum contact performance. There have been three operating conditions linked to this variation in contact voltage:

- Insufficient contact pressure
- degradation of one of the contact surfaces
- extreme surface heating which results in contact surface softening

Lubrication

The lubricant found to be most compatible with the Westinghouse contact and the intended operation was DuPont's Krytox fluorinated grease. Krytox is chemically inert over the design temperature range and provides the lubrication essential for optimum contact wear-in. However, during a number of deliberately slow cooldowns, shots with very high but stable contact voltage drops were observed. These events occurred only for new contacts and

temperature range of $200 \pm 20^\circ\text{K}$. This effect was finally traced to a Krytox characteristic which had not been documented. In the range of 200°K the Krytox forms brittle nodules. Between the time these nodules were formed and the time they were mechanically reduced and excluded from the contact area, the RMS contact voltage gradually increased and then returned to the nominal levels. Figure 20 shows this effect beginning at shot number 290 and ending by shot 299.

Contact Resistance as a Function of Temperature

Figure 20 also illustrates the contact pulse resistance as a function of temperature. The single contact assembly was mechanically cycled two hundred times and then the power system was adjusted to provide a very repeatable 650 A at room temperature, indicated as 285°K . With the power system at a fixed setting (and dominated by series resistance), and the repetition time at one minute, a cooldown was started. The lowest trend panel on Figure 20 clearly indicates the magnitude of the change in pulse resistance:

at 285°K , single contact resistance = $80\ \mu\text{ohm}$

at 80°K , single contact resistance = $180\ \mu\text{ohm}$.

A numerical model of the contact electrical behavior is being formulated. There are two temperature sensitive components which account for the sliding contact resistance behavior. The first element is the body resistance of the contact. It is well documented that as the copper temperature decreases from room temperature to 2N_2 , the copper resistance decreases by a factor of 6.5. This element of the resistance model however is overwhelmed by the sliding metal to metal resistance which increases as the temperature is lowered.

Contact Resistance as a Function of Contact Current

Considerable work was done in characterizing the contact resistance as a function of current density in the contact. Figure 21 shows the resistance of a single contact as current and pulse duration are varied. The data presented represent 148 shots with multiple shots occurring at identical current levels.

The four pulse durations displayed are one, three, ten, and fifteen seconds and are stacked in that order (top to bottom) on the left-hand extreme of Figure 21.

Four, six, and eight second pulses which were not counted in the 148 shots were deleted from the figure for clarity but fell within the band of the data presented.

Figure 22 is a comparable plot of resistance vs. contact current for the twenty-four contact assembly. A total of 87 ten second shots are plotted for two different series of shots (solid circle and open circle).

The data in Figs. 21 and 22 are consistent in that for comparable current densities the slope (change in resistance per change in contact current) of the curves agree within a few percent.

Failure Point

A considerable number of single contacts were operated to very high values of current for a 1 sec duration and moderate levels for a 10 sec duration. Temperature-related failures were induced in a number of single contacts. The failure mode always involved the melting of the contact silver plating. In the majority of the cases, the silver wetted the stainless guide pin in the contact and on the next shot prevented the contact from mechanically floating. When the contact was mechanically bound during the subsequent shot, minimum contact pressure was lost and contact burn resulted. Contact burn would take the form of surface melting, sometimes penetrating the silver plating to the extent that copper melting and then welding would occur. In no instance was the resultant weld of any significant strength since the weld material is limited to a combination of copper and silver, an alloy family noted for its low tensile strength.

Significant effort was aimed at defining the failure threshold. Figure 23 shows a contact which experienced slight surface silver melting yet in subsequent shots showed no compromise in resistance or temperature excursion characteristics. The contact body temperature was monitored by an embedded thermocouple (see Figure 23 for location). The peak indicated contact body temperature was 1050° K for a 4 kA, 3 sec shot, equivalent to an i^2t of $48 \times 10^6 \text{ A}^2 \cdot \text{s}$. This combination of current and pulse duration was found to be the most severe set of parameters which did not result in a failure. Two other combinations, both of which led to an indicated body temperature of 900°K were:

- 5.5 kA for one second, equivalent to $30 \times 10^6 \text{ A}^2 \cdot \text{s}$,

- 25 kA for ten seconds, equivalent to $62 \times 10^6 \text{A}^2 \cdot \text{s}$.

Figure 23 clearly shows in the first and third frames that the melt leading edge is perpendicular to the direction of current flow and most extensive in the center of the contact which is thermally most isolated. The second and fourth frames show that the actual electrical contact areas are unaffected.

Conclusion

The purpose of this program was to investigate the engineering feasibility of a sliding electrical joint within the constraints posed by the Ignition Studies Project configuration designated 1025.

The conclusion is that one sliding joint design which incorporates the Westinghouse contact is viable and offers a significant operating margin. The following is a partial comparison of the parameter levels required by the 1025 design and those demonstrated in extensive operating experience.

	Required by 1025 Design	Demonstrated	Margin to Failure
Current per contact, one second duration	0.825 kA	5.5 kA	>6x
Current per contact long pulse average	0.5 kA, 16s	3 kA, 15s	6x
Thermal (i^2t) rating per contact, one sec duration, ($\text{A}^2 \cdot \text{s}$)	0.7×10^6	$>30 \times 10^6$	>40x
Thermal (i^2t) rating per contact, long pulse $\text{A}^2 \cdot \text{s}$	4.7×10^6 16s	$>100 \times 10^6$ 15s	>20x

Other performance factors such as temperature excursion, contact pulse resistance, power dissipation, and contact voltage drop have been thoroughly characterized and do not present any design constraints relative to 1025. A number of other factors specific to the sliding joint design such as lubrication, surface plating, and joint assembly details are now understood and are viable, conceptually to the 1025 point design.

Definitive feasibility, however, can only be demonstrated in a test which incorporates the following essential elements:

- a statistically meaningful basis

- a background magnetic field

Future work would be aimed at these two factors in addition to a number of techniques which appear promising in further extending the operating margin.

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	<u>Per Zone</u>	<u>Per Contact</u>
i^2t , one second		
peak	$41 \times 10^6 \text{ A}^2 \cdot \text{s}$	$0.7 \times 10^6 \text{ A}^2 \cdot \text{s}$
i^2t , 16 second		
cumulative	$285 \times 10^6 \text{ A}^2 \cdot \text{s}$	$4.75 \times 10^6 \text{ A}^2 \cdot \text{s}$
current, one		
second peak	50 kA	825 A
current, sixteen		
second, average	30 kA	500 A

TABLE 1

FIGURE 1 - TOKAMAK CONFIGURATION

VACUUM VESSEL

FIGURE 2 - TOKAMAK DURING ASSEMBLY

FIGURE 3 - TF CONDUCTOR CURRENT DENSITY DISTRIBUTION - WITH TIME

Peak $I^{*2}t$ In Zone (Amp *2 sec x 10^{*6}) Double Sided

ZONE #	TIME																Average per Zone (16 sec)	Peak per Zone (1 sec)
10	2.4	4.1	4.1	2.2	0.7	0.0	1.2	5.7	28.9	28.2	24.1	23.4	41.0	17.3	8.6	5.7	197.6	41.0
9	1.2	1.8	1.5	0.1	0.0	1.0	3.6	9.4	26.1	25.4	22.8	22.8	28.2	17.3	9.0	3.6	199.9	23.2
8	0.1	0.1	0.1	0.0	1.0	1.5	7.4	14.0	24.1	22.7	21.5	21.5	21.5	24.0	6.7	2.2	168.4	24.1
7	0.0	0.0	0.2	1.0	3.6	7.8	12.5	17.8	20.8	20.8	20.8	20.8	16.7	10.2	11.6	1.0	163.6	20.8
6	0.0	0.1	1.8	4.1	7.4	11.6	16.1	20.2	19.0	19.0	18.4	18.4	11.6	6.0	2.0	0.1	155.8	20.2
5	0.3	2.0	4.7	8.2	12.6	16.7	19.6	22.1	17.3	16.7	15.6	15.6	7.4	3.1	0.6	0.0	162.5	22.1
4	1.0	4.7	9.4	14.0	17.3	20.2	22.1	24.1	15.6	15.1	14.0	13.5	4.1	1.0	0.0	1.0	177.1	24.1
3	2.9	9.4	15.1	19.6	20.8	22.7	24.1	25.4	14.0	13.6	12.5	11.6	2.9	0.0	1.8	2.9	199.3	25.4
2	7.4	16.7	22.7	24.7	26.2	26.2	26.2	26.2	12.5	12.5	11.6	10.2	0.4	0.3	1.8	5.7	231.3	26.2
1	14.0	25.4	30.5	30.5	30.5	30.5	30.5	12.5	12.5	10.7	10.2	0.0	1.5	4.7	9.8		284.3	30.5

Peak Current / Contact in Zone (Amps) Double Sided

ZONE #	TIME																Average per Zone (16 sec)	Peak per Zone (1 sec)
10	-101	-263	-263	-193	-103	0	140	335	695	686	633	625	826	533	378	416	263	826
9	-140	-177	-158	-38	0	131	246	336	660	650	616	616	667	533	386	246	288	667
8	-88	-28	-51	-16	131	158	350	483	623	616	598	598	598	483	434	193	315	623
7	0	0	51	131	246	360	430	545	583	583	583	528	413	440	151	352	583	583
6	26	88	176	263	350	440	516	583	561	561	505	505	440	316	183	53	348	583
5	79	185	280	366	350	533	566	533	536	528	510	510	350	228	96	-26	352	566
4	131	281	396	483	533	580	600	633	510	501	483	475	261	151	18	-151	368	600
3	220	395	501	571	583	611	633	650	483	475	458	440	220	53	-176	-220	367	650
2	351	528	615	650	660	660	660	660	450	458	440	413	78	-70	-176	-308	379	660
1	483	650	713	721	721	721	721	713	458	458	421	413	27	-158	-281	-405	497	721

FIGURE 4 - SLIDING JOINT LAYOUT WITH $I^{*2}t$ AND I PEAK TABULATION

FIGURE 5 - SLIDING JOINT CONCEPT WITH CONTACT DETAILS

FIGURE 6 - TWENTY-FOUR CONTACT TEST ASSEMBLY

FIGURE 7 - PPPL HIGH CURRENT TEST FACILITY

FIGURE 8 - TEST STAND WITH WESTINGHOUSE CONTACT
AND G10 DEWAR FOR LN_2

FIGURE 9 - IN-LINE ASSEMBLY USED TO TEST SINGLE, SIX, EIGHT
AND TWELVE WESTINGHOUSE CONTACTS

FIGURE 10 - TWENTY-FOUR CONTACT ASSEMBLY
EXTENSIVE OPERATION AT 25KA

FIGURE 11 - SINGLE CONTACT ASSEMBLY-TEMPERATURE RISE
VS CONTACT CURRENT VS PULSE DURATION

FIGURE 12- SIX CONTACT ASSEMBLY-TEMPERATURE RISE VS CONTACT CURRENT

FIGURE 13 - TWENTY-FOUR CONTACT ASSEMBLY-
 TEMPERATURE RISE VS CONTACT CURRENT

**FIGURE 14 - TWENTY-FOUR CONTACT ASSEMBLY-
 TEMPERATURE RISE VS CONTACT CURRENT**

FIGURE 15 - SINGLE CONTACT ASSEMBLY-COOLDOWN TO N_2 AND EXCERPT OF I^2t CAPABILITY MAP

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FIGURE 16 - SINGLE CONTACT ASSEMBLY-I-V-T WAVE FORMS
FOR 2.7kA SHOTS OF 6, 10 AND 14.5s DURATION

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FIGURE 17 - SINGLE CONTACT ASSEMBLY-
I-V-T WAVEFORMS FOR 2.7KA SHOTS OF 1, 2 AND 4s DURATION

#86E0071

FIGURE 18 - SINGLE CONTACT ASSEMBLY-

CURRENT (3KA) AND TEMPERATURE WAVEFORMS FOR 15s DURATION PULSE

FIGURE 19 - TWENTY-FOUR CONTACT ASSEMBLY-
I-V-T WAVEFORMS FOR 10s DURATION PULSE

FIGURE 20 - SINGLE CONTACT ASSEMBLY-
COOLDOWN STUDY OF CONTACT RESISTANCE AND LUBRICANT BEHAVIOR

FIGURE 21 - SINGLE CONTACT ASSEMBLY-
CONTACT RESISTANCE VARIATION WITH CONTACT CURRENT AND PULSE DURATION

FIGURE 22 - TWENTY-FOUR CONTACT ASSEMBLY-
ASSEMBLY RESISTANCE VARIATION WITH CURRENT PER CONTACT

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Single Contact Experienced Pulse of
4 kA/3 sec/1050° K Without Failure

FIGURE 23

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